SIMULATION STUDIES FOR REPLENISHMENT AT SEA OPERATION

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THESIS

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by

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at Sea Operation

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ABSTRACT

This study investigates the maneuvering of ships involved in the replenishment at sea operation under calm water conditions.

Two sets of linear differential equations of motion of a ship in three degrees of freedom are implemented for an analog-digital simulation (hybrid operation). Mainly a two phase hybrid simulation is carried out.

In the first part the real-time dynamic response of a single ship is obtained. Small perturbations, resulting from small changes in rudder angle and propeller RPM, are studied.

In the second part interaction forces and moments are applied only to the leading ship as it is overtaken by the tracking ship. Thus the response of the leading ship is of primary interest on this phase.

Finally interaction forces and moments are applied to both leading and tracking ship. Thus the complete response of the UNREP operation is obtained.

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TABLE OF SYMBOLS

C	=	Stability criterion for stability in straight line motion
I_x, I_y, I_z	=	Moments of inertia about the X, Y, Z axes, respectively
K, M, N	=	Rolling, pitching, and yawing moments, respectively
L	=	Ship length between perpendiculars (LBP)
m	=	Mass of ship
p, q, r	=	Angular velocities of roll, pitch, and yaw, respectively
$\vec{U}$	=	Velocity of the origin of the body axes relative to the fluid
$t, \Delta t$	=	Time and time interval, respectively
u, v, w	=	Velocity components of the origin of the body axes relative to the fluid (longitudinal, and normal components, respectively
u_1	=	Initial equilibrium velocity component (ahead straight line motion at constant speed with rudder at amidships)
Δu	=	$u - u_2$
$\dot{u}, \dot{v}, \dot{w}$	=	Acceleration components of the origin of the body axes relative to the fluid (longitudinal, transverse, and normal components, respectively
X, Y, Z	=	Hydrodynamic force components in ship body (longitudinal, lateral and normal components)
x, y, z	=	Coordinate axes fixed in ship. Origin of axes system need not be at the center of gravity of the ship (positive direction forward, starboard, and downward, respectively

x_G, y_G, z_G = Coordinates of the center of mass of the ship relative to body axes

x_o, y_o, z_o = Coordinates relative to the coordinate system fixed in the earth

$x_{o_G}, y_{o_G}, z_{o_G}$ = Coordinates of the center of mass of the ship relative to the coordinate system fixed in the earth

β = Angle of drift. Lateral side to side separation distance between ships

δ = Angular displacement of a control surface, normal to the rudder angle

ϕ, θ, ψ = Angles of roll, pitch, and yaw, respectively

ρ = Mass density (mass density if sea water is 1.9905 lb-sec

$\dot{x}_o, \dot{y}_o, \dot{z}_o$ = Velocity components of the ship axes relative to the space coordinate system

α = Longitudinal separation distance between midships

Δn = Small change in RPM propeller speed

ΔR = Small change in rudder angle

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I. INTRODUCTION

At the present time the operational procedure of replenishment at sea underway is described by two manuals of the Department of the Navy [1] and [2]. This procedure includes collision hazard. Therefore an analysis of the replenishment operations may provide a mean for improvement of ship maneuvering and ship control. The maneuver of replenishment at sea involves six factors: course, speed, distance between ships, the approach, station keeping and departure.

This thesis describes the analysis of underway replenishment (UNREP) using an analog computer simulation. This analog computer simulation model will describe two Mariner Class merchant ships. An effort is made to define the control parameters necessary to provide information for the conning officer and/or helmsman which will increase the safety conditions of the UNREP operation. According to the tactical requirements the UNREP operation is interpreted as follows:

a. The replenishing (leading) ship is responsible for course keeping only.

b. The receiving (tracking) ship is responsible for both course and station (distance between ships) keeping.

For this reason one ship is constrained to move in a straight line course at constant speed. The rudder and

propeller of the second ship are controlled in order to keep it in a parallel course relative to the first ship.

The analog computer output is presented and analyzed to determine the necessary information for the ship control parameters required during these simulated UNREP operations.

II. INTERACTION EFFECTS

When underway, the pressure distribution on the ship hull varies (as is shown in Figure 1) due to the variable velocity of the water flow, the so-called venturi effect.

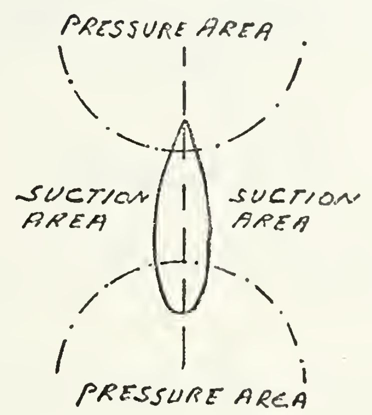


Figure 1. Pressure distribution on the hull.

When two ships are alongside underway, this venturi effect is increased and becomes more complicated due to the mixing of the pressure areas of two ships.

Figure 2 shows ships which are in dangerous position because they are being acted on by radically different pressures. Reduction of speed increases the danger of collision. Also the pressure effects are more exaggerated and extra care is required in maneuvering (in depths less than 20 fathoms).

It is understood that to maintain station during UNREP operation a certain amount of rudder is required

which depends on size, load, sea conditions, speed and ship separation. But this change of rudder deflection

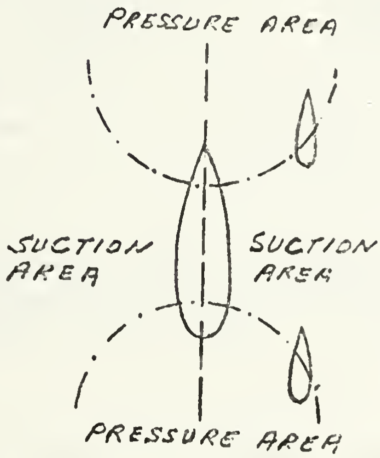


Figure 2. Ships alongside underway.

decreases handling capabilities of the receiving ship.

The problem of interaction effects has been studied theoretically by Silverstein [3] and experimentally by Newton [4] with both approaches showing agreement in the general conclusions.

When two ships are underway with a certain separation and on parallel courses, the pressure fields mix which results in an unbalanced force and moment on each ship. This interaction moment must be cancelled by the rudder action in order to maintain station. However, there is a position where the rudder force tends to add to the force of attraction, see Figure 3. Thus in these positions a bigger rudder deflection is required so the yaw angle produced in this way creates an outboard force

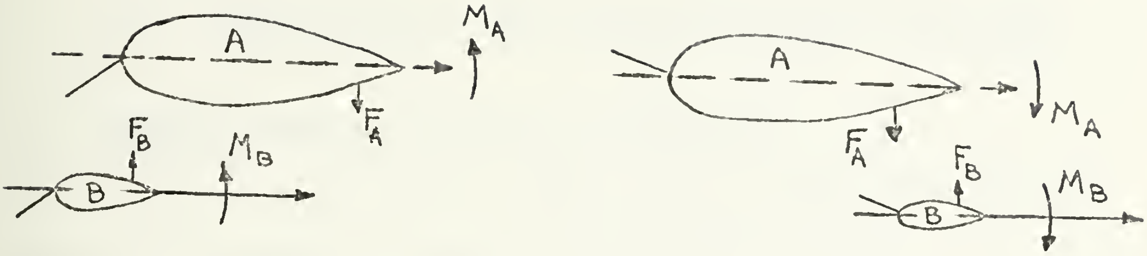


Figure 3. Relative position where both interaction forces and moments tend to draw one ship toward the other.

which balances both the rudder and interaction force.

Newton's experiment, both with models and full scale trials in open sea, prove one important thing: It is the process of approach or departure from the abeam or "fueling" position that includes the maneuvering risks. It should be noted here that an increase in velocity or decrease of separation between ships results in the increase of the interaction effects.

III. DERIVATION OF THE LINEAR MATHEMATICAL MODEL

A. GENERAL CASE—SIX DEGREES OF FREEDOM

It is well understood that the coordinate-axes system fixed on the ship's body is an Eulerian system. It is assumed that at t=0 the Eulerian system and the space coordinates system coincide, as shown in Figure 4. The geo-

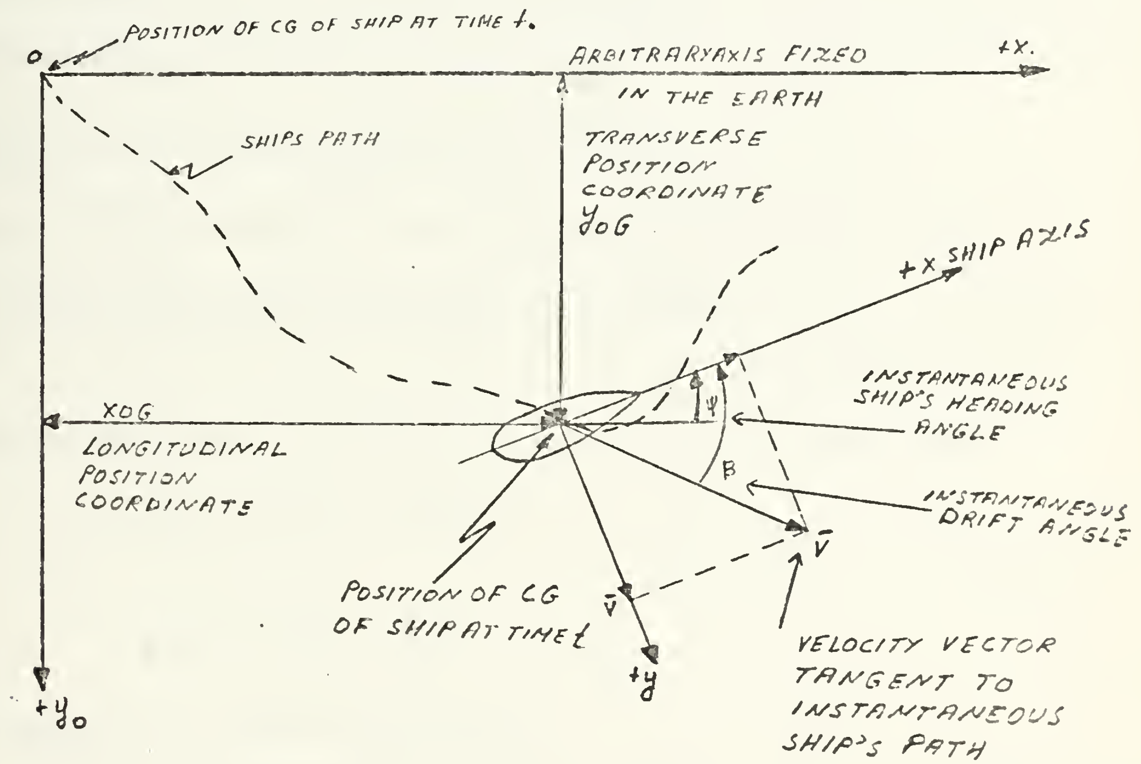


Figure 4. Orientation of fixed axes and moving axes.

graphic coordinate system then describes the motion of the ship through the fluid medium in six degrees of freedom.

The Newton's laws of motion in vector form are:

$$\vec{F} \text{ (External Force)} = \frac{d}{dt}\,(\overrightarrow{\text{momentum}})$$

$$\vec{M} \text{ (External Moment)} = \frac{d}{dt}\,(\overrightarrow{\text{angular momentum}}) \qquad \text{(III-1)}$$

Then the six equations (six degrees of freedom) describing the ship's motion have been found [5]

$$X=m[\dot{u}+qw-rv-x_G(r^2+q^2)+y_G(pq-\dot{r})+z_G(pr+\dot{q})]$$

$$Y=m[\dot{v}+ru-pw-y_G(r^2+p^2)+z_G(qr-\dot{p})+x_G(qp+\dot{v})]$$

$$Z=m[\dot{w}+pv-qu-z_G(p^2+q^2)+x_G(rp-\dot{q})+y_G(rp+\dot{p})]$$

$$K=\dot{p}I_X+(I_Z-I_Y)qr+m[y_G(\dot{w}-qu+pv)-z_G(\dot{v}-pw+rv)]$$

$$M=\dot{q}I_Y+(I_X-I_Z)pr+m[z_G(\dot{u}-rv+qw)-x_G(\dot{w}-qu+pv)]$$

$$N=\dot{r}I_Z+(I_Y-I_X)pq+m[x_G(\dot{v}-pw+ru)-y_G(\dot{u}-rv+qw)] \qquad \text{(III-2)}$$

Using (III-2) the following equations can be satisfied:

$$\vec{F} = \hat{i}X + \hat{j}Y + \hat{k}Z$$

$$\text{(III-3)}$$

$$\vec{M} = \hat{i}K + \hat{j}M + \hat{k}N$$

and where: m – mass of the ship

X, Y, Z – components of force in the x,y,z directions

K, M, N – components of applied moment about x,y,z axes

u, v, w – components of velocity in the x,y,z directions

x_G, y_G, z_G – distances of origin from center of gravity in x,y,z directions

p, q, r — components of angular velocity about the x,y,z axes

I_x, I_y, I_z — moments of inertia about the x,y,z axes

Equation (III-2) describes the reaction of the rigid body of the ship itself as a function of its geometric and physical characteristics. Note that they do not include any external moments such as due to fins.

B. HORIZONTAL PLANE MOTION

It is well understood that the ship's motion in calm waters is described only by the following four equations:

$$X = m[\dot{u}+qu-rv-x_G(r^2+q^2)+y_G(pq-\dot{r})+z_G(pr+\dot{q})], \text{ surge}$$

$$Y = m[\dot{v}+ru-pw-y_G(r^2+p^2)+z_G(qr-\dot{p})+x_G(qp+\dot{r})], \text{ sway}$$

$$N = \dot{r}I_z+(I_y-I_x)pq+m[x_G(\dot{v}-pw+ru)-y_G(\dot{u}-rv+qw)], \text{ yaw}$$

$$K = \dot{p}I_x+(I_z-I_y)qr+m(y_G(\dot{w}-qu+pv)-z_G(\dot{v}-pw+rv)], \text{ roll} \quad \text{(III-4)}$$

because under the calm water assumption it is true that Roll = Pitch = Heave = 0. That is the horizontal motion implies: $p = \dot{p} = q = \dot{q} = w = \dot{w} = 0$. Hence the equations (III-4) can be written:

$$X = m[\dot{u}-rv-x_G r^2-y_G\dot{r}]$$

$$Y = m[\dot{v}+ur+x_G\dot{r}-y_G r^2]$$

$$K = m[-z_G(\dot{v}+rv)]$$

$$N = \dot{r}I_z+m[x_G(\dot{v}+ru)-y_G(\dot{u}-rv)] \quad \text{(III-5)}$$

Equations (III-5) can be further simplified assuming that the center of gravity (CG) is placed at the origin

of the x, y, z coordinate system then $x_G = y_G = z_G = 0$. Hence, neglecting the roll equation we have:

$$X = m[\dot{u}-rv], \text{ surge}$$

$$Y = m[\dot{v}+ur], \text{ sway}$$

$$N = \dot{r}I_z \quad , \text{ yaw} \qquad \text{(III-6)}$$

There are the reduced equations for steering and maneuvering of a ship. It is noted that the left hand side of equations (III-6) represents the forces and moment along the coordinate axes, and the right hand side shows the corresponding dynamic response terms on the horizontal plane of motion.

C. LINEARIZATION THROUGH TAYLOR'S SERIES EXPANSION [5],[6]

The forces and moments on the left hand side of equations (III-1) through (III-6) can be expressed as functions of properties of the body, properties of the fluid and motion.

Since steering and maneuvering are of interest, forces and moments are also considered as functions of rudder (control surface) deflections and the change in r.p.m. (Δn) of the propeller shaft. Thus:

$$\left.\begin{array}{l}\text{Forces}\\ \text{Moments}\end{array}\right\} = f(\text{properties of motion, rudder deflection, etc.}) = f(\underbrace{x_o, y_o, z_o, \phi, \theta, \psi}_{\text{orientation parameters}}, \underbrace{u, v, w, p, q, r, \dot{u}, \dot{v}, \dot{w}, \dot{p}, \dot{q}, \dot{r}}_{\text{motion parameters}}, \underbrace{\delta, \dot{\delta}, \ddot{\delta}, \Delta n}_{\text{control surface parameters}}, \text{ etc.}) \qquad \text{(III-7)}$$

For a surface ship moving on the horizontal plane no forces or moments are due to orientation changes. Thus the forces and moments will be functions of three degrees of freedom of motion parameters, rudder deflection parameters and changes in r.p.m. Hence:

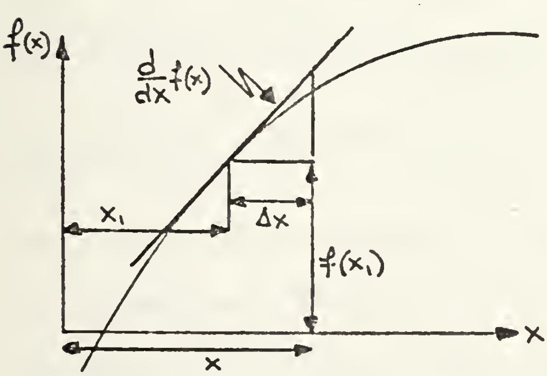
$$\left.\begin{array}{l} X \\ Y \\ N \end{array}\right\} = f\,(u, v, r, \dot{u}, \dot{v}, \dot{r}, \delta, \dot{\delta}, \ddot{\delta}, \Delta n, \text{ etc.}) \qquad \text{(III-8)}$$

In general we linearize a function f(x) by the use of Taylor's series expansion.

$$f(x) = f(x_1) + \frac{\Delta x}{1!}\frac{df(x)}{dx} + \ldots \div \frac{\Delta x^n}{n!}\frac{d^n f(x)}{dx^n}$$

where $\quad \Delta x = x - x_1$

For small values of Δx the second order terms can be neglected and thus considering only the following expression for f(x):



$$f(x) = f(x_1) + \Delta x \frac{df(x)}{dx} \qquad \text{(III-9)}$$

This is the linearized Taylor's series expansion. The same principle can be applied for small perturbations in the equation (III-8), which is a function of many variables.

Since the Taylor expansion is written for a particular point we choose this point to be an equilibrium position. An equilibrium position is that of straight ahead motion, at constant speed with rudder amidships. The hydrodynamic forces and moment have been found [6] to be:

$$X = X_u \Delta u + X_v v + X_r r + X_{\dot{u}} \dot{u} + X_{\dot{v}} \dot{v} + X_{\dot{r}} \dot{r} + X_\delta \delta + X_n \Delta n$$

where $\Delta u = u - u_1$ and $\Delta n = n - n_1$ and the subscript 1 is referred to the values of the variables at the initial equilibrium condition and where all the partial derivatives are evaluated. For Y and N similar expressions hold. Equating the linearized expression for X, Y, and N with equation (III-6) results in the linearized equations of motion for steering and maneuvering:

$$X_u \Delta u + X_v v + X_r r + X_{\dot{u}} \dot{u} + X_{\dot{v}} \dot{v} + X_{\dot{r}} \dot{r} + X_\delta \delta + X_n \Delta n = m\dot{u}$$

$$Y_u \Delta u + Y_v v + Y_r r + Y_{\dot{u}} \dot{u} + Y_{\dot{v}} \dot{v} + Y_{\dot{r}} \dot{r} + Y_\delta \delta + Y_n \Delta n = m(\dot{v} + r u_1)$$

$$N_u \Delta u + N_v v + N_r r + N_{\dot{u}} \dot{u} + N_{\dot{v}} \dot{v} + N_{\dot{r}} \dot{r} + N_\delta \delta + N_n \Delta n = I_z \dot{r} \qquad \text{(III-10)}$$

Note that the term mvr in the right hand side of the first of equations (III-6) has been dropped since the ship was assumed in straight ahead motion. The derivatives

$$X_v,\ X_{\dot{v}},\ X_r,\ X_{\dot{r}},\ X_\delta$$

$$Y_u,\ Y_{\dot{u}}$$

and N_u, $N_{\dot{u}}$ vanish for any symmetrical port and starboard shape of ship (symmetry about the xz-plane). This has the effect of decoupling surge from sway and yaw. Thus equations (III-10) become:

$$(X_{\dot{u}}-m)\dot{u}+X_u\Delta u+X_n\Delta n = 0$$

$$(Y_{\dot{v}}-m)\dot{v}+Y_v v+(Y_r-mu_1)r+Y_{\dot{r}}\dot{r}+Y_\delta\delta+Y_n\Delta n = 0$$

$$(N_{\dot{r}}-I_z)\dot{r}+N_v v+N_{\dot{v}}\dot{v}+N_r r+N_\delta\delta+N_n\Delta n = 0 \qquad \text{(III-11)}$$

Using as a basis the linear mathematical model of equations (III-11) the criterion for dynamic stability in straight line motion [5] is evaluated as

$$C = Y_v N_r - N_v(Y_r-mu_1) > 0$$

It is obvious that the treatment of the linear mathematical model, for the study of a dynamically stable ship, can be applied to predict maneuvering and control only for small deviations from the original straight line motion due to small rudder deflections and small changes in r.p.m.

D. NON-DIMENSIONAL EQUATIONS

Table I gives the dimensionalized, nondimensionalized quantities and their respective conversion factors. The prime notation corresponds to the nondimensionalized quantities. In equations (III-10)the force equations are divided by $(\rho/2)L^2u_1^2$ and the moment equation by $(\rho/2)L^3u_1^2$.

The resulting nondimensional equations are:

$$(X'_{\dot{u}} - m')\dot{u}' + X'_u \Delta'_u + X'_n \Delta' n = 0$$

$$(Y'_{\dot{v}} - m')\dot{v}' + Y'_v v' + (Y'_r - m' u'_1) r' + Y'_{\dot{r}} r' + Y'_\delta \delta' + Y'_n \Delta' n = 0$$

$$(N'_{\dot{r}} - I'_z)\dot{r}' + N'_v v' + N'_{\dot{v}} v' + N'_r r' + N'_\delta \delta' + N'_n \delta' n = 0 \qquad \text{(IV-1)}$$

It is noted here that

$$\frac{u_1}{|\vec{U}|} \approx 1.0$$

for small perturbations.

TABLE I

NONDIMENSIONAL NOMENCLATURE

Symbol	Non-Dimensional Form	Definition
$X_{\dot{u}}$	$X'_{\dot{u}} = \frac{X_{\dot{u}}}{\frac{1}{2}\rho L^2 u_1}$	Derivative of longitudinal force component with respect to longitudinal acceleration component u
X_u	$X'_u = \frac{X_u}{\frac{1}{2}\rho L^2 u_1}$	Derivative of longitudinal force component with respect to longitudinal velocity component u
Y_v	$Y'_v = \frac{Y_v}{\frac{1}{2}\rho L^2 u_1}$	Derivative of lateral force component with respect to transverse velocity component
$Y_{\dot{v}}$	$Y'_{\dot{v}} = \frac{Y_{\dot{v}}}{\frac{1}{2}\rho L^3}$	Derivative of lateral force component with respect to transverse acceleration component
Y_r	$Y'_r = \frac{Y_r}{\frac{1}{2}\rho L^3 u_1}$	Derivative of lateral force component with respect to yaw angular velocity component
$Y_{\dot{r}}$	$Y_{\dot{r}} = \frac{Y_{\dot{r}}}{\frac{1}{2}\rho L^4}$	Derivative of lateral force component with respect to yaw angular acceleration component
Y_δ	$Y'_\delta = \frac{Y_\delta}{\frac{1}{2}\rho L^2 u_1^2}$	Derivative of lateral force component with respect to rudder angle component

N_v	$N'_v = \frac{N_v}{\frac{1}{2}\rho L^3 u_1}$	Derivative of yawing moment component with respect to transverse velocity component
$N_{\dot{v}}$	$N'_{\dot{v}} = \frac{N_{\dot{v}}}{\frac{1}{2}\rho L^4}$	Derivative of yawing moment component with respect to transverse velocity component
N_r	$N'_r = \frac{N_r}{\frac{1}{2}\rho L^4 u_1}$	Derivative of yawing component with respect to yaw angular velocity component
$N_{\dot{r}}$	$N'_{\dot{r}} \quad \frac{N_{\dot{r}}}{\frac{1}{2}\rho\ L^5}$	Derivative of yawing moment with respect to yaw angular acceleration component
N_δ	$N'_\delta \quad \frac{N_\delta}{\frac{1}{2}\rho L^3 u_1^2}$	Derivative of yaw moment component with respect to rudder angle component
X_n	$X'_n = \frac{X_n}{\frac{1}{2}\rho L^3 u_1}$	Derivative of longitudinal force component with respect to change in propeller rpm
Y_n	$Y'_n = \frac{Y_n}{\frac{1}{2}\rho L^3 u_1}$	Derivative of lateral force change in with respect to propeller rpm
N_n	$N'_n = \frac{N_n}{\frac{1}{2}\rho L^4 u_1}$	Derivative of yawing component with respect to change in propeller rpm
r	$r' = \frac{rL}{U}$	Yawing angular velocity component
$\dot{r}$	$\dot{r}' = \frac{\dot{r}L^2}{U^2}$	Yawing angular acceleration component

U	$U' = 1$	Velocity of origin of body axes relative to fluid
v	$v' = \frac{v}{U}$	Transverse velocity component of origin of ship axes relative to fluid
$\dot{v}$	$\dot{v}' = \frac{\dot{v}L}{U^2}$	Transverse acceleration component of ship axes relative to fluid
X	$X' = \frac{X}{\frac{1}{2}\rho L^2 u_1^2}$	Hydrodynamic longitudinal force (positive direction forward)
Y	$Y' = \frac{Y}{\frac{1}{2}\rho L^2 u_1^2}$	Hydrodynamic lateral force (positive direction to starboard)
m	$m' = \frac{m}{\frac{1}{2}\rho L^3}$	Mass of the ship
u	$u' = \frac{u}{U}$	Velocity of origin of ship's axes along the x-axis
$\dot{u}$	$\dot{u}' = \frac{\dot{u}L}{U^2}$	Acceleration of origin of ship's axes along the x-axis
I_z	$I'_z = \frac{m}{\frac{1}{2}\rho L^5}$	Moment of inertia of the ship with respect to the z-axis

IV. AXES FIXED RELATIVE TO THE EARTH—LANGRANGIAN SYSTEM

To convert equations (III—6) from the Eulerian system to the Langrangian system, see Figure 4, the stationary coordinate system, the total forces in the x and y direction in the ship coordinates must be expressed in terms of the stationary coordinates as follows:

$$X = X_o \cos \psi + Y_o \sin \psi$$

$$Y = Y_o \cos \psi + X_o \sin \psi \qquad \text{(V-1)}$$

Also the center of gravity possesses velocity and acceleration with respect to the stationary coordinate system expressed as follows:

$$\dot{x}_{o_G} = u \cos \psi - v \sin \psi$$

$$\dot{y}_{o_G} = u \sin \psi + v \cos \psi \qquad \text{(V-2)}$$

and

$$\ddot{x}_{o_G} = \dot{u} \cos \psi - \dot{v} \sin \psi - (u \sin \psi + v \cos \psi)\dot{\psi}$$

$$\ddot{y}_{o_G} = \dot{u} \sin \psi + \dot{v} \cos \psi + (u \cos \psi - v \sin \psi)\dot{\psi}$$

$$\text{(V-3)}$$

Equations (V—2) can be used to calculate the trajectory and velocity of the ship with respect to stationary coordinate system. Equations (V—3) can be used to calculate the acceleration along this trajectory.

V. ANALOG COMPUTER PROGRAMMING FOR EACH SHIP INDEPENDENTLY

A. PRELIMINARY STUDY

In this section we will discuss the simulation of the ship dynamics in open calm sea. The equations of motion for each ship are programmed independently and no interaction forces and moments are considered.

1. Linearized Equations of Motion

Equations (IV-1) are repeated here for convenience as follows:

$$(m'-X'_{\dot{u}})\dot{u}' = X'_u u' + X'_n \delta n, \text{ Surge}$$

$$(m'-Y'_{\dot{v}})\dot{v}' = Y'_v v' + (Y'_{\psi}-m'u'_o)\dot{\psi}' + Y'_{\ddot{\psi}}\ddot{\psi}' + Y'_n \delta'_n + Y'_{\delta R}\delta R', \text{ Sway}$$

$$(I'_z-N'_{\dot{\psi}})\ddot{\psi}' = N'_v v' + N'_{\dot{\psi}}\dot{\psi}' N'_{\dot{v}}\dot{v}' + N'_{\delta R}\delta R' + N'_n \delta n', \text{ Yaw} \qquad (V-1)$$

where

$$r = \dot{\psi}$$

$$\dot{r} = \ddot{\psi}$$

$$N_{\delta} = N_{\delta R}$$

$$\Delta n = \delta n$$

$$u_o = u_1$$

It is noted here again that all the variables correspond to small perturbation variables. It is first chosen

the equilibrium condition as follows:

Nominal values: $\dot{x}_o$ = 15 knots = 25.32 ft/sec = u_o

$v_o = 0$

$\psi_o = 0$

2. Magnitude Scaling of the Linearized Equations

Following the usual procedure each equation of equations (V-1) is scaled by letting each variable be represented by its maximum value times the scaled variable. That is:

$$\dot{u} = \dot{u}_m \bar{\dot{u}}$$

and in non-dimensional form:

$$\dot{u}' = \dot{u}'_m \bar{\dot{u}}'$$

where: $\dot{u}_m$ is the maximum expected value

$\bar{\dot{u}}$ is the scaled variable whose value ranges from -1 to +1 computer units (i.e. $\pm$ 100 volts for CI-5000 analog computer).

Makint this substitution for all the variables in equations (V-1) and solving for the scaled variables $\bar{\dot{u}}$, $\bar{\dot{v}}$, and $\bar{\ddot{\psi}}$ we obtain:

$$\bar{\dot{u}} = \left[\frac{X'_u u'_m}{(m'-X'_{\dot{u}})\dot{u}'_m}\right]\bar{u}' + \left[\frac{X'_n \delta n'_m}{(m'-X'_{\dot{u}})\dot{u}'_m}\right] \delta\bar{n}'$$

$$\bar{\dot{v}} = \left[\frac{Y'_v v'_m}{(m'-Y'_{\dot{v}})\dot{v}'_m}\right]\bar{v}' + \left[\frac{(Y'_{\dot{\psi}}-m'u_o)\dot{\psi}'_m}{(m'-Y'_{\dot{v}})\dot{v}'_m}\right]\bar{\dot{\psi}}' + \left[\frac{Y'_{\ddot{\psi}} \ddot{\psi}'_m}{(m'-Y'_{\dot{v}})\dot{v}'_m}\right] \bar{\ddot{\psi}}'$$

$$+ \left[\frac{Y'_{\delta R}\delta R'_m}{(m'-Y'_{\dot{v}})\dot{v}'_m}\right]\overline{\delta R}' + \left[\frac{Y'_n \delta n'_m}{(m'-Y'_{\dot{v}})\dot{v}'_m}\right]\overline{\delta n}'$$

$$\bar{\ddot{\psi}}' = \left[\frac{N'_v \; v'_m}{(I'_z - N'_{\dot\psi} \; \ddot{\psi}'_m}\right] \bar{v}' + \left[\frac{N'_{\dot\psi} \; \dot{\psi}'_m}{(I'_z - N'_{\dot\psi})\ddot{\psi}'_m}\right] \bar{\dot\psi}'$$

$$+ \left[\frac{N'_{\dot v} \; \dot{v}'_m}{(I'_z - N') \; '_m}\right] \bar{\dot v}' + \left[\frac{N'_{\delta R} \delta R'_m}{(I'_z - N'_{\dot\psi})\ddot{\psi}'_m}\right] \bar{\delta R}'$$

$$+ \left[\frac{N'_n \delta n'_m}{(I'_z - N'_{\dot\psi})\ddot{\psi}'_m}\right] \bar{\delta n}' \; , \qquad \text{(V-2)}$$

Letting each term in brackets be a coefficient (k), equations (V-2) can be written as:

$$\bar{\dot u}' = -k_{11}\bar{u}' + k_{12}\bar{\delta n}'$$

$$\bar{\dot v}' = -k_{15}\bar{v}' - k_{16}\bar{\dot\psi}' - k_{17}\bar{\ddot\psi} + k_{18}\bar{\delta R}' - k_{19}\bar{\delta n}'$$

$$\bar{\ddot\psi} = -k_{111}\bar{v}' - k_{112}\bar{\dot\psi}' - k_{113}\bar{\dot v}' - k_{114}\bar{\delta R}' + k_{115}\bar{\delta n}' \qquad \text{(V-3)}$$

where the appropriate sign has been extracted so that each coefficient is now positive. Table IV gives the nondimensional values necessary for equation (V-2) and (V-3). The following data are also given in Table II.

TABLE II

u_o = 25.32 ft/sec (nominal ship's velocity)

u_o^2 = 640.0 $(\text{ft/sec})^2$; ρ = 2 lbs sec^2/ft^4; L = 527.87 ft

$\frac{1}{2}\rho L^3 u_o^2$ = 9.428E+10; $\frac{1}{2}\rho L^2 u_o^2$ = 17.86E+07

$\frac{1}{2}\rho L^5$ = 4.095E+13; $\frac{1}{2}\rho L^3$=1.4707E+07; $\frac{1}{2}\rho L^2$=2.7862E+05

3. Calculation of Potentiometer Coefficients

In obtaining a set of scaled equations, it is best to work with dimensional quantities. Actually, scaling the nondimensional equations is equivalent to scaling the dimensional set. Tables III through V give all the necessary data for the scaling procedure. Referring to dimensional quantities equations (V-2) can be rewritten as:

$$\bar{\dot{u}} = \left[\frac{X_u \; u_m}{(m-X_{\dot{u}})\,\dot{u}_m}\right]\bar{u} + \left[\frac{X_n \,\delta n_m}{(m-X_{\dot{u}})\,\dot{u}_m}\right]\overline{\delta n}, \text{ Surge}$$

$$\bar{\dot{u}} = \left[\frac{Y_v \; v_m}{(m-Y_{\dot{v}})\,\dot{v}_m}\right]\bar{v} + \left[\frac{(Y_{\dot{\psi}}-mu_o)\,\dot{\psi}_m}{(m-Y_{\dot{v}})\,\dot{v}_m}\right]\bar{\dot{\psi}}$$

$$+ \left[\frac{Y_{\ddot{\psi}} \; \ddot{\psi}_m}{(m-Y_{\dot{v}})\,\dot{v}_m}\right]\bar{\ddot{\psi}} + \left[\frac{Y_{\delta R} \; \delta R_m}{(m-Y_{\dot{v}})\,\dot{v}_m}\right]\overline{\delta R}$$

$$+ \left[\frac{Y_n \,\delta n_m}{(m-Y_{\dot{v}})\,\dot{v}_m}\right]\overline{\delta n}, \text{ Sway}$$

$$\bar{\ddot{\psi}} = \left[\frac{N_v \; v_m}{(I_z-N_{\ddot{\psi}})\,\ddot{\psi}_m}\right]\bar{v} + \left[\frac{N_{\dot{\psi}} \; \dot{\psi}_m}{(I_z-N_{\ddot{\psi}})\,\ddot{\psi}_m}\right]\bar{\dot{\psi}} + \left[\frac{N_{\dot{v}} \; \dot{v}_m}{(I_z-N_{\ddot{\psi}})\,\ddot{\psi}_m}\right]\bar{\dot{v}}$$

$$+ \left[\frac{N_{\delta R} \; R_m}{(I_z-N_{\ddot{\psi}})\,\ddot{\psi}_m}\right]\overline{\delta R} + \left[\frac{N_n \; n_m}{(I_z-N_{\ddot{\psi}})\,\ddot{\psi}_m}\right]\overline{\delta n}, \text{ Yaw} \qquad \text{(V-4)}$$

Let $D_{11} = (m-X_{\dot{u}})\,\dot{u}_m = m\dot{u}_m - X_{\dot{u}}\dot{u}_m$

$= (1.166 \times 10^6 \text{ slugs} \times 0.844 \text{ ft/sec}^2$

$+ 1.0295 \times 10^5 \text{ lbs/ft/sec}^2 \times 0.844 \text{ ft/sec}^2)$

$= 0.984 \times 10^6 + 0.0866 \times 10^6 = 1.07 \times 10^6 \text{ lbs}$

$D_{12} = (m-Y_{\dot{v}})\,\dot{v}_m = m\dot{v}_m - Y_{\dot{v}}\dot{v}_m$

$= 1.66 \times 10^6 \times 0.844 + 1.043 \times 10^6 \times 0.844$

$= 0.984 \times 10^6 + 0.880 \times 10^6 = 1.864 \times 10^6 \text{ lbs}$

$$D_{13} = (I_z - N_{\ddot{\psi}})\ddot{\psi}_m = I_z\ddot{\psi}_m - N_{\ddot{\psi}}\ddot{\psi}_m$$

$$= 1.43 \times 10^{10} \text{ lbs ft/rad/sec}^2 \times 0.87 \times 10^{-3} \text{rad/sec}^2$$

$$= 1.244 \times 10^7 + 1.533 \times 10^7 = 2.777 \times 10^7 \text{ lbs-ft}$$

Then from equations (V-3) and (V-4)

$$K_{11} = \left[\frac{X_u u_m}{D_{11}}\right] = \left[\frac{-8.465 \times 10^3 \text{lbs/ft/sec} \times 5.064 \text{ ft/sec}}{1.07 \times 10^6 \text{ lbs}}\right]$$

$$= \frac{-42.866 \times 10^3}{1.07 \times 10^6} = -40.0623 \times 10^{-3} = -0.040623$$

$$K_{12} = \left[\frac{X_n \delta n_m}{D_{11}}\right] = \left[\frac{1.72 \times 10^5 \text{lbs/rev/sec} \times 30\text{rpm} \times \frac{\text{rec/sec}}{60\text{rpm}}}{1.07 \times 10^6 \text{ lbs}}\right]$$

$$= \frac{1.72 \times 10^5 \times 0.5}{1.07 \times 10^6} = 0.08037$$

$$K_{15} = \left[\frac{Y_v v_m}{D_{12}}\right] = \left[\frac{-8.76 \times 10^4 \text{lbs/ft/sec} \times 5.064 \text{ ft/sec}}{1.864 \times 10^6 \text{ lbs}}\right]$$

$$= \frac{-44.36 \times 10^4}{1.864 \times 10^6} = -23.798 \times 10^{-2} = -0.23798$$

$$K_{16} = \left[\frac{(Y_{\dot{\psi}} - mu_o)\dot{\psi}_m}{D_{12}}\right] = \left[\frac{Y_{\dot{\psi}}\dot{\psi} - mu_o \dot{\psi}_m}{D_{12}}\right]$$

$$= \left[\frac{1.042\text{x}10^7 \text{lbs/rad/sec} \times 3.49\text{x}10^{-2} \text{rad/sec} - 1.166\text{x}10^6 \frac{\text{lbs}}{\text{ft/sec}^2} \times 25.32 \text{ft/sec} \times 3.49\text{x}10^{-2} \text{rad/sec}}{1.864 \times 10^6 \text{ lbs}}\right]$$

$$= \left[\frac{3.6365\text{x}10^5 - 29.5\text{x}10^6 \times 3.49\text{x}10^{-2}}{1.864 \times 10^6}\right] = \left[\frac{3.6365\text{x}10^5 - 10.303\text{x}10^5}{1.864 \times 10^6}\right]$$

$$= \frac{-6.66\text{x}10^5}{1.864\text{x}10^6} = -3.5762 \times 10^{-1} = -0.35762$$

$$K_{17} = [\frac{Y_{\ddot{\psi}}\ddot{\psi}_m}{D_{12}}] = [\frac{-2.096\text{x}10^7 \frac{\text{lbs}}{\text{rad/sec}^2} \text{x} 0.87\text{x}10^3 \frac{\text{lbs}}{\text{rad/sec}^2}}{1.864 \text{ x } 10^6 \text{ lbs}}]$$

$$= \frac{1.82 \text{ x } 10^4}{1.864\text{x } 10^6} = -0.9764\text{x}10^{-2} = -0.009764$$

$$K_{18} = [\frac{Y_{\delta R}\delta R_m}{D_{12}}] = [\frac{4.823\text{x}10^5 \text{lbs/rad x } 0.35 \text{ rad}}{1.864 \text{ x } 10^6}]$$

$$= \frac{1.688 \text{ x } 10^5}{1.864 \text{ x } 10^6} = 0.090558$$

$$K_{19} = [\frac{Y_n \delta n_m}{D_{12}}] = [\frac{-1.936\text{x}10^4 \frac{\text{lbs}}{\text{rev/sec}} \text{ x } 30\text{rpm} \frac{\text{rev/sec}}{60 \text{ rpm}}}{1.864 \text{ x } 10^6 \text{ lbs}}]$$

$$= \frac{-1.936\text{x}10^4\text{x}0.5}{1.864 \text{ x } 10^6} = \frac{-0.968\text{x}10^4}{1.864\text{x}10^6} = -0.005193$$

$$K_{111} = [\frac{N_v v_m}{D_{13}}] = [\frac{-1.307\text{x}10^7 \text{ft/ft/sec x } 5.064 \text{ ft/sec}}{2.777 \text{ x } 10^7 \text{ lbs-ft}}]$$

$$= \frac{-6.6186\text{x}10^6}{2.777\text{x}10^7} = -2.3834 \text{ or } -0.23834 \text{ into a gain of } 10$$

$$K_{112} = [\frac{N_{\dot{\psi}}\dot{\psi}_m}{D_{13}}] = [\frac{-4.462\text{x}10^9 \frac{\text{lbs-ft}}{\text{rad/sec}} \text{ x } 3.49\text{x}10^{-2} \text{rad/sec}}{2.777 \text{ x } 10^7 \text{ lbs-ft}}]$$

$$= \frac{-15.5723\text{x}10^7}{2.777\text{x}10^7} = -5.6076 \text{ or } -0.56076 \text{ into a gain of } 10$$

$$K_{113} = [\frac{N_{\dot{v}} \dot{v}_m}{D_{13}}] = [\frac{-1.552\text{x}10^7 \frac{\text{lbs-ft}}{\text{ft/sec}^2} \text{ x } 0.844 \text{ ft/sec}^2}{2.777 \text{ x } 10^7 \text{ lbs-ft}}]$$

$$= \frac{-1.30988\text{x}10^7}{2.777\text{x}10^7} = -0.47169$$

$$K_{114} = [\frac{N_{\delta R}\delta R_m}{D_{13}}] = [\frac{-1.188\text{x}10^8 \frac{\text{lbs-ft}}{\text{rad}} \text{ x } 0.35 \text{ rad}}{2.777 \text{ x } 10^7 \text{ lbs-ft}}]$$

$$= \frac{-4.158\text{x}10^7}{2.777\text{x}10^7} = -1.497 \text{ or } -0.1497 \text{ into a gain of } 10$$

$$K_{115} = \left[\frac{N_{n}^{\delta n_{m}}}{D_{13}}\right] = \left[\frac{5.110\times10^{6}\,\frac{\text{lbs-ft}}{\text{rev/sec}} \times 30\text{RPM}\,\frac{\text{rev/sec}}{60\text{RPM}}}{2.777 \times 10^{7}\ \text{lbs-ft}}\right]$$

$$= \frac{5.11 \times 10^{6}\times 0.5}{2.777 \times 10^{7}} = \frac{2.555 \times 10^{6}}{2.777 \times 10^{7}} = 0.0920$$

The calculated potentiometer values are summarized in Table VI.

Making use of the k's coefficients, equations (V–4) can be written as follows:

$$\bar{\dot{u}} = k_{11}\bar{u} + k_{12}\overline{\delta n} \qquad \text{(V–4a)}$$

$$\bar{\dot{v}} = k_{15}\bar{v} + k_{16}\bar{\dot{\psi}} + k_{17}\bar{\ddot{\psi}} + k_{18}\overline{\delta R} + k_{19}\overline{\delta n}$$

$$\bar{\ddot{\psi}} = k_{111}\bar{v} + k_{112}\bar{\dot{\psi}} + k_{113}\bar{\dot{v}} + k_{114}\overline{\delta R} + k_{115}\overline{\delta n}$$

Analog programming of these equations will give the left hand side quantities but sign inverted, because summer amplifiers and integrators invert the sign of their input quantities. Hence for analog programming equations (V–4a) are written as follows next:

$$\bar{\dot{u}} = -[k_{11}\ \bar{u} + k_{12}\ \overline{\delta n}] \qquad \text{(V–4b)}$$

$$\bar{\dot{v}} = -[k_{15}\ \bar{v} + k_{16}\ \bar{\dot{\psi}} + k_{17}\ \bar{\ddot{\psi}} + k_{18}\ \overline{\delta R} + k_{19}\ \overline{\delta n}]$$

$$\bar{\ddot{\psi}} = -[k_{111}\bar{v} + k_{112}\bar{\dot{\psi}} + k_{113}\bar{\dot{v}} + k_{114}\overline{\delta R} + k_{115}\overline{\delta n}]$$

Equations (V–4b) can be written as follows after taking care of the actual sign of each coefficient as already have been calculated previously:

$$\bar{\dot{u}} = k_{11}\ \bar{u} - k_{12}\ \overline{\delta n} \qquad \text{(V–4c)}$$

$$\bar{\dot{v}} = k_{15}\ \bar{v} + k_{16}\ \bar{\dot{\psi}} + k_{17}\ \bar{\ddot{\psi}} - k_{18}\ \overline{\delta R} + k_{19}\ \overline{\delta n}$$

$$\bar{\ddot{\psi}} = k_{111}\bar{v} + k_{112}\bar{\dot{\psi}} + k_{113}\bar{\dot{v}} + k_{114}\overline{\delta R} + k_{115}\overline{\delta n}$$

Equations (V-4c) are finally programmed in the analog CI-5000 computer.

TABLE III

DERIVATIVE	DIMENSIONAL VALUE
$Y_{\dot{\psi}}$	1.042×10^{7} lbs/rad/sec
$Y_{\ddot{\psi}}$	-2.096×10^{7} lbs/rad/sec^2
Y_{v}	-8.76×10^{4} lbs/ft/sec
$Y_{\dot{v}}$	-1.083×10^{6} lbs/ft/sec^2
N_{v}	-1.307×10^{7} lbs-ft/ft/sec
$N_{\dot{v}}$	-1.552×10^{7} lbs-ft/ft/sec^2
Y_{n}	-1.936×10^{4} lbs/rev/sec
$N_{\ddot{\psi}}$	-1.762×10^{10} lbs-ft/rad/sec^2
$Y_{\delta R}$	4.823×10^{5} lbs/rad
$N_{\delta R}$	-1.188×10^{8} lbs-ft/rad
X_{u}	-8.465×10^{3} lbs/ft/sec
$X_{\dot{u}}$	-1.0295×10^{5} lbs/ft/sec^2
X_{n}	1.720×10^{5} lbs/rev/sec
N_{n}	5.110×10^{6} lbs-ft/rev/sec
$N_{\dot{\psi}}$	-4.462×10^{9} lbs-ft/rad/sec

TABLE IV

DERIVATIVE	NON–DIMEN. FACTOR	NON–DIMEN. VALUE
$(X_{\dot{u}} - m)$	$\frac{1}{2}pL^3$	-850×10^{-5}
$(Y_{\dot{v}} - m)$	$\frac{1}{2}pL^3$	-1500×10^{-5}
$(Y_{\dot{\psi}} - m\ u_o)$	$\frac{1}{2}pL^3u_o$	-510×10^{-5}
$(N_{\ddot{\psi}} - I_z)$	$\frac{1}{2}pL^5$	-77.9×10^{-5}
$Y_{\dot{\psi}}$	$\frac{1}{2}pL^3u_o$	.0028
$Y_{\ddot{\psi}}$	$\frac{1}{2}pL^4$	−.0027
Y_v	$\frac{1}{2}pL^2u_o$	−.01243
$Y_{\dot{v}}$	$\frac{1}{2}pL^3$	−0.0071
$N_{\dot{v}}$	$\frac{1}{2}pL^4$	−.0002
N_v	$\frac{1}{2}pL^3u_o$	−.0035
Y_n	$\frac{1}{2}pL^3u_o$	−.0000052
$N_{\ddot{\psi}}$	$\frac{1}{2}pL^5$	−.00043
$Y_{\delta R}$	$\frac{1}{2}pL^2u_o^2$	.0027
$N_{\delta R}$	$\frac{1}{2}pL^3u_o^2$	−.00126
X_u	$\frac{1}{2}pL^2u_o$	−.0012
$X_{\dot{u}}$	$\frac{1}{2}pL^3$	−.0007
X_n	$\frac{1}{2}pL^3u_o$	.00005
N_n	$\frac{1}{2}pL^4u_o$	−.0000026
$N_{\dot{\psi}}$	$\frac{1}{2}pL^4u_o$	−.00227
m	$\frac{1}{2}pL^3$	.0079

TABLE V

PARAMETERS AND MAXIMUM VALUES

$m_1 = 1.26 \times 10^6$ (slugs) — mass of ship with entrained water

$m = m_1/1.08 = 1.166$ (slugs) — mass of ship itself only

$I_z = 1.43 \times 10^6$ Inertia (slugs — FT2)

$\psi_m = 0.26$ Yaw Angle (RAD) = 14.9 (degrees)

$\dot{\psi}_m = 0.0349$ Yaw Vel. (RAD/SEC) = 2 DEG/SEC

$\ddot{\psi}_m = 0.00087$ Yaw Accel. (RAD/SEC^2) = 0.05 DEG/SEC^2

$\dot{x}_{om} = 5.064 = \dot{y}_{om}$ (FT/SEC)

$\ddot{x}_{om} = 0.844 = \ddot{y}_{om}$ (FT/SEC^2)

$x_{om} = 550$ (FT)

$\delta R_m = 20$ Rudder Defelction (DEG) = 0.35 (RAD)

$\delta n_m = 30$ Propeller Speed (RPM) = (RAD/SEC) = $\frac{1}{2}$(REV/SEC)

$y_{om} = 160$ (FT)

$L = 527.85$ Ship Length (FT)

TABLE VI

COEFFICIENT VALUES

$k_{11} = 0.0404623$

$k_{12} = 0.08037$

$k_{15} = 0.23798$

$k_{16} = 0.35762$

$k_{17} = 0.009764$

$k_{18} = 0.090558$

$k_{19} = 0.005193$

$k_{111} = 0.23834$ (into a gain of 10)

$k_{112} = 0.56076$ (into a gain of 10)

$k_{113} = 0.47169$

$k_{114} = 0.1497$ (into a gain of 10)

$k_{115} = 0.0920$

For ship No 2 the following relationships hold:

$k_{21} = k_{11}$

$k_{22} = k_{12}$ etc.

TABLE VII

MARINER CHARACTERISTICS

Length, ft.	528.5
Beam, ft.	76.0
Draft, ft.	29.75
Displacement, tons	20.900
Block Coefficient C_b	.6125
Prismatic Coeff. C_p	.6246
Midships Section Coeff. C_m	.9807

4. Analog Patching Configuration

a. Static Test

(1) Ship No 1. Figure 5 shows the analog patching used for the static test. The 9300 digital machine was used for this job. Computer program IA contains the source deck of the program as well as the print out. Table VIII gives the values of parameters as used.

(2) Ship No 2. Figure 6 shows the analog patching used for the static test. Computer program IB gives the source deck and Table IX gives the values of parameters as used.

The static test was satisfactory since the printed values were the correct expected ones. As

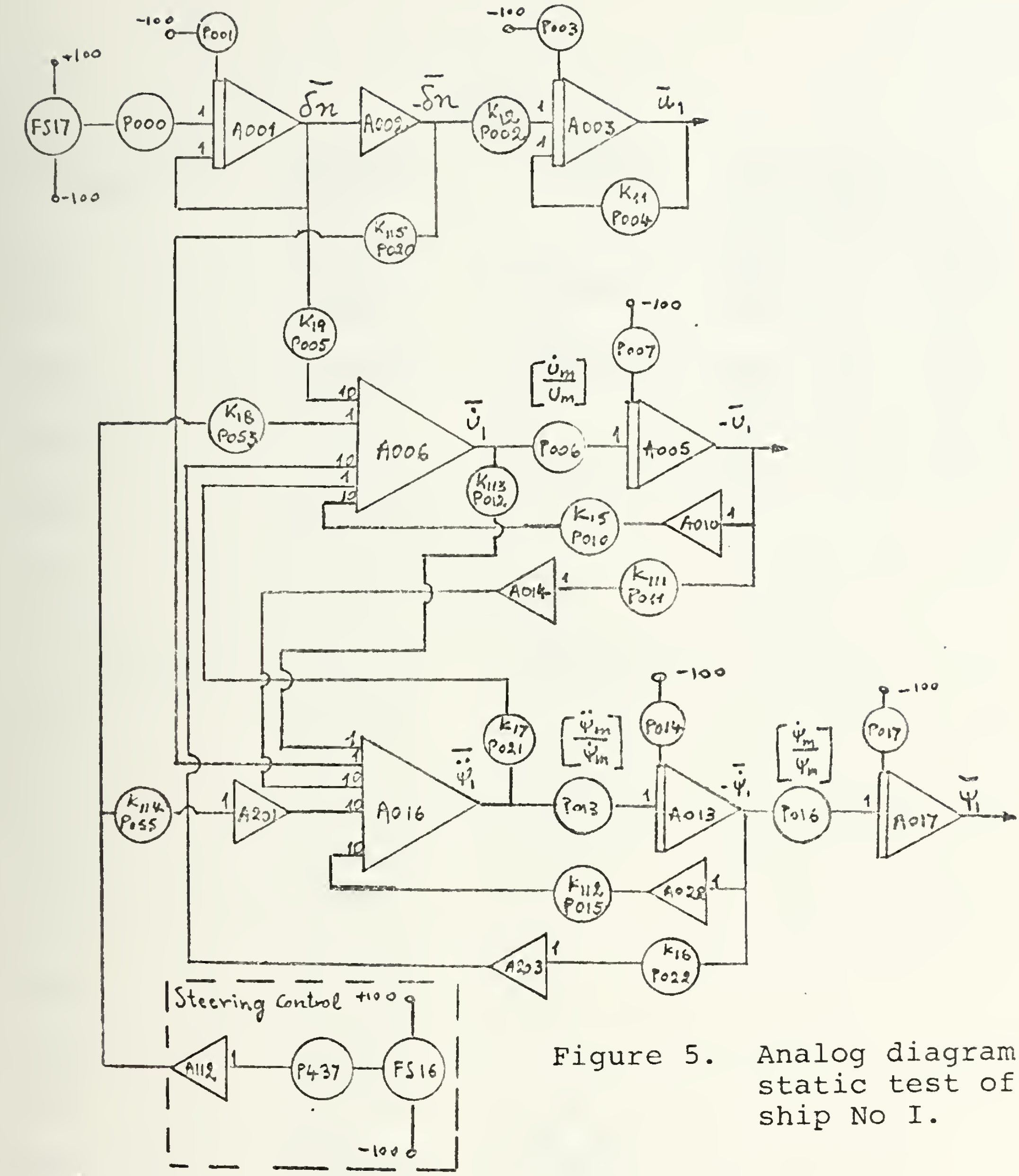
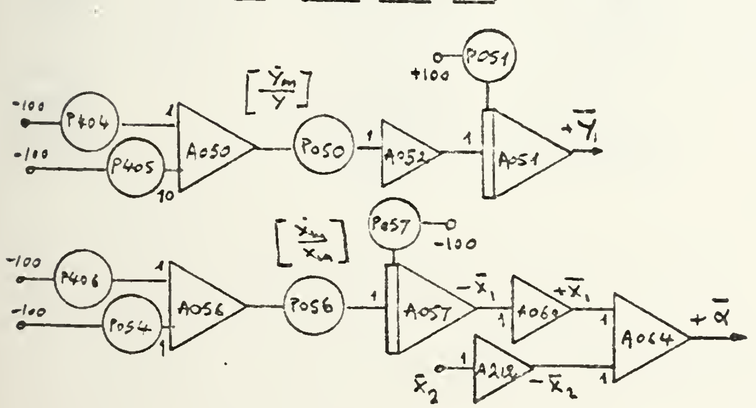


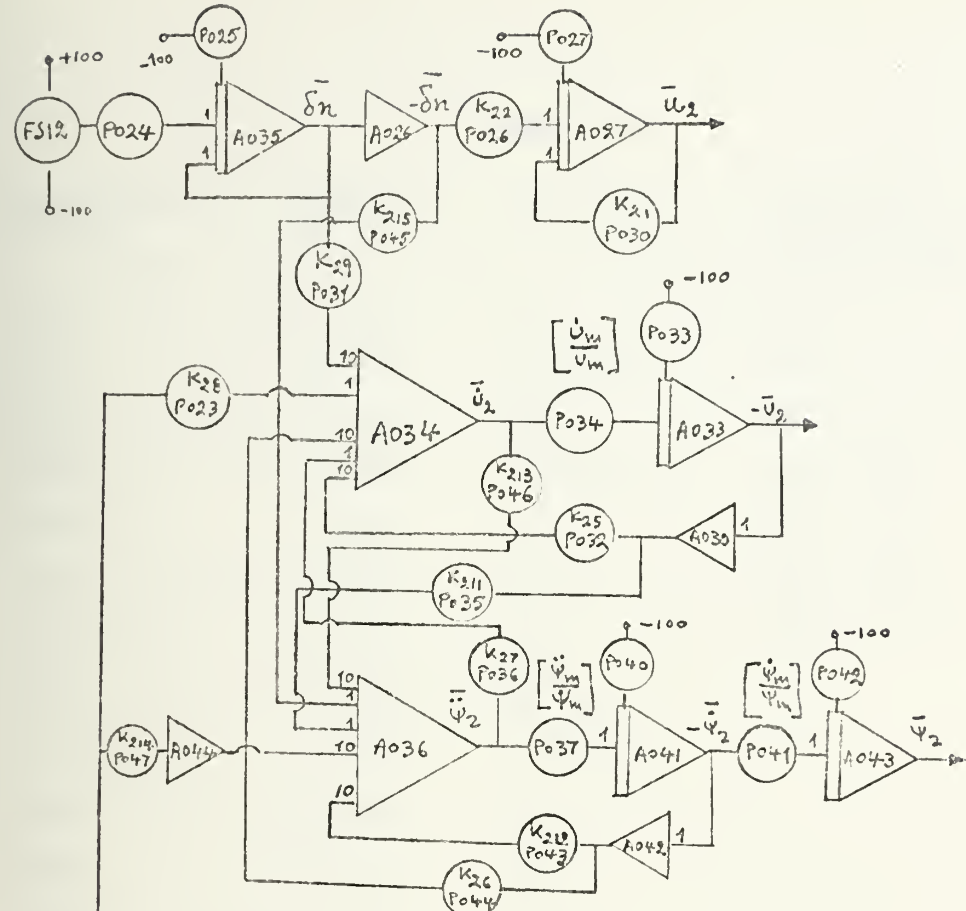
Figure 5. Analog diagram for static test of ship No I.



After the coordinates transformation

TABLE VIII

Potentiometer Address	Adjusted Value	Parameter	Assigned I.C. of integrators for static test
P000	0.1000	Δn	A001 3. volts
P001	0.0300	IC—A001	A003 6. volts
P002	0.0803	K_{12}	A005 9. volts
P003	0.0600	IC—A003	A013 12. volts
P004	0.0404	K_{11}	A017 15. volts
P005	0.0052	K_{19}	A051 3. volts
P007	0.0900	IC—A005	A057 45.4 volts
P010	0.2379	K_{15}	
P011	0.2383	K_{111}	
P012	0.4717	K_{113}	
P013	0.0250	$[\ddot{\psi}_m/\psi_m]$	
P014	0.1200	IC—A013	
P015	0.5607	K_{112}	
P016	0.1340	$[\dot{\psi}_m/\psi_m]$	
P017	0.1500	IC—A017	
P020	0.0920	K_{115}	
P021	0.0097	K_{17}	
P022	0.3576	K_{16}	
P053	0.0905	K_{18}	
P054	0.0500		
P055	0.1497	K_{114}	
P050	0.0337	$[\dot{y}_m/y_m]$	
P051	0.3000	IC—A051	
P056	0.0092	$[\dot{x}_m/x_m]$	
P057	0.4540	IC—A057	
P437	0.1000	ΔR	
P006	0.1660	$[\dot{u}_m/u_m]$	



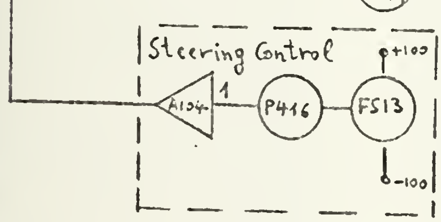
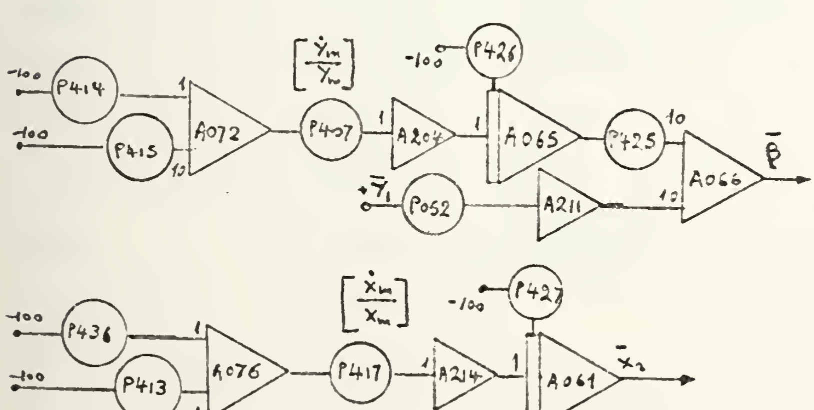


Figure 6. Analog diagram for static test of ship No 2.

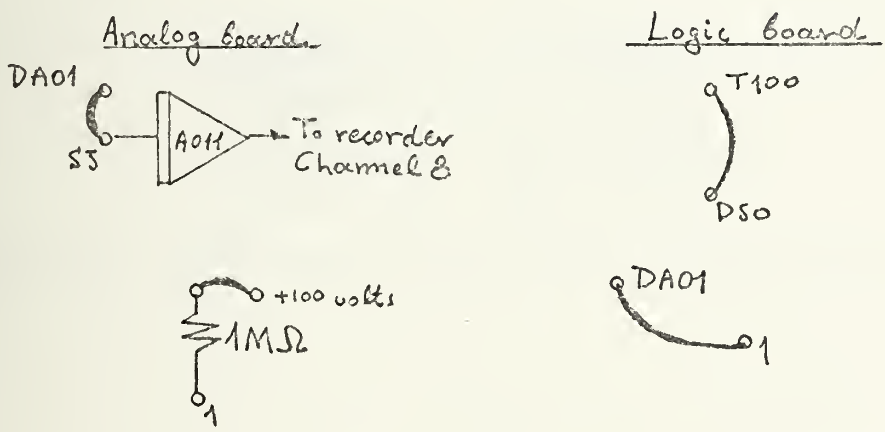


After the coordinates transformation

TABLE IX

Potentiometer Address	Adjusted Values	Parameter	Assigned I.C. to integrator for static test
P024	0.1000	Δn	A035 3. volts
P025	0.0300	IC–A035	A027 6. volts
P026	0.0803	K_{22}	A033 9. volts
P027	0.0600	IC–A027	A041 12. volts
P030	0.0404	K_{21}	A043 15. volts
P045	0.0920	K_{215}	A065 30. volts
P031	0.0052	K_{29}	A061 54.5 volts
P023	0.0905	K_{28}	
P034	0.1660	$[\dot{u}_m/u_m]$	
P033	0.0900	IC–A033	
P046	0.4717	K_{213}	
P032	0.2379	K_{25}	
P035	0.2383	K_{211}	
P047	0.1497	K_{214}	
P036	0.0097	K_{27}	
P037	0.0250	$[\ddot{\psi}_m/\dot{\psi}_m]$	
P040	0.1200	IC–A041	
P041	0.1340	$[\dot{\psi}_m/\psi_m]$	
P042	0.1500	IC–A043	
P043	0.5607	K_{212}	
P044	0.3576	K_{26}	
P407	0.0337	$[\dot{y}_m/y_m]$	
P425	0.3000	IC–A065	
P426	0.5000		
P052	0.5000		
P417	0.0092	$[\dot{x}_m/x_m]$	
P427	0.5450	IC–A061	
P416	0.1000	ΔR	

far as the logic board is concerned Figure 6c shows the wiring necessary for the amplifier's operation where RT means real time and is connected to a capacitor of 1μF. This Figure was made for amplifier A001 and A003, but this is true for all the amplifiers used. Also, Figure 6d shows the logic operation for the amplifiers A001 and A003, which is again true for all the amplifiers used.



B. CHARACTERISTIC LINEAR RESPONSE OF MARINER

First of all, amplifier A011 was used as a timer for the 8th channel of the chart recorder. The wiring was as shown above.

So by this configuration, a pulse was recorded every 1 sec, i.e., every one time unit.

Figures 7 and 8 show the analog patching diagrams used to obtain the responses of ship 1 and 2, respectively. These response curves are shown in a later section. At this time interaction forces and moments are not included.

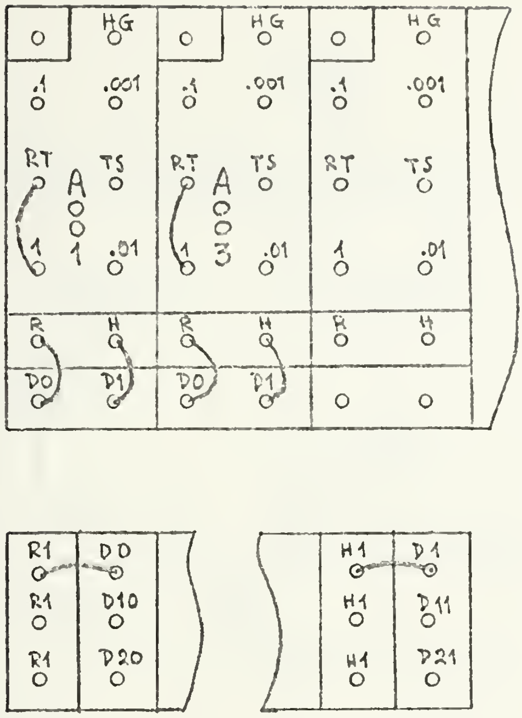


Figure 6c. Logic patching diagram for the amplifiers used.

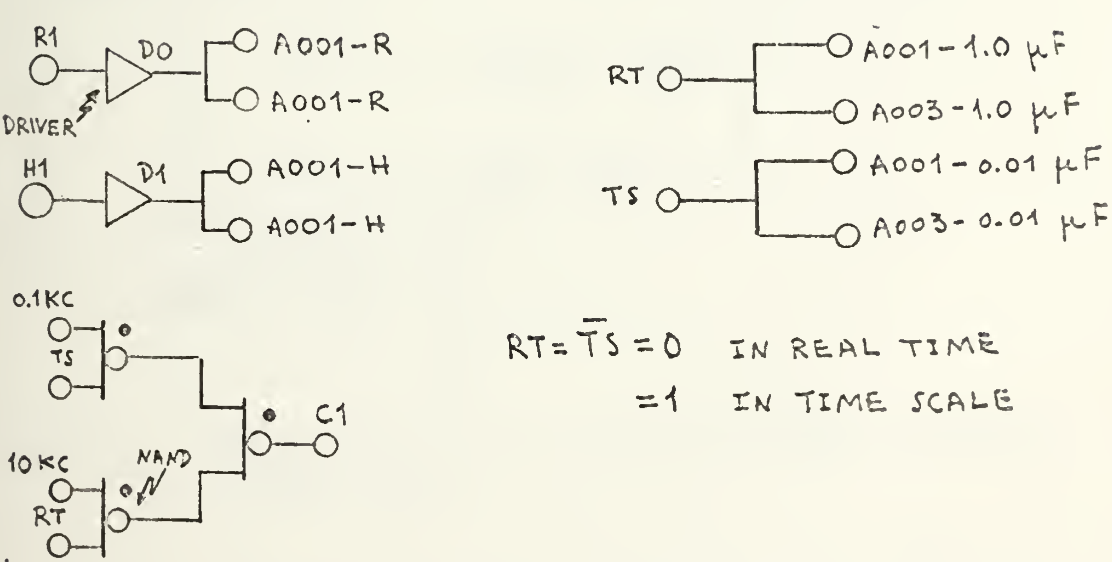


Figure 6d. Schematic diagram of amplifier's logic operation regarding the feedback capacitor.

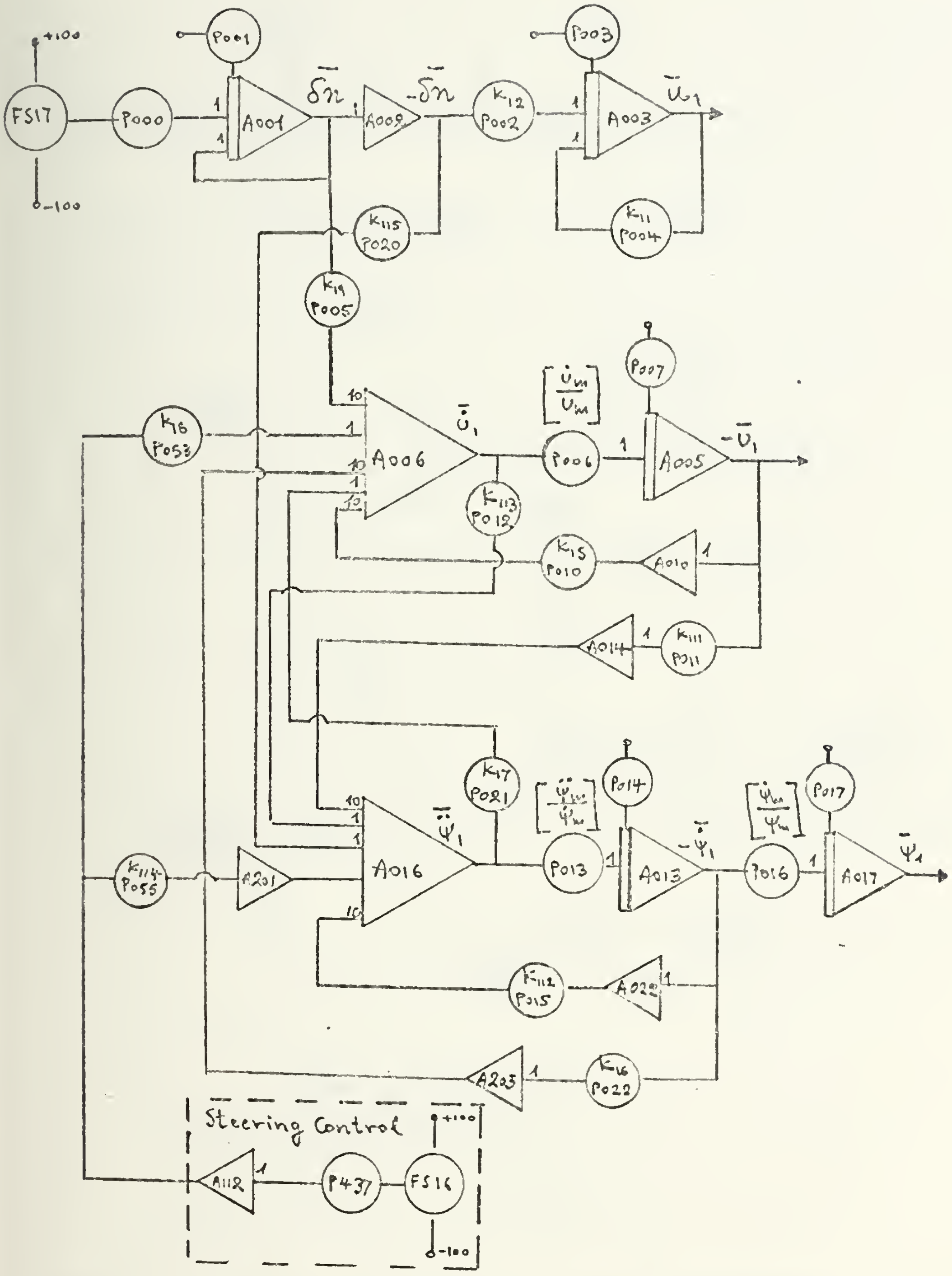


Figure 7. Analog diagram for study of dynamic behavior of ship No. 1.

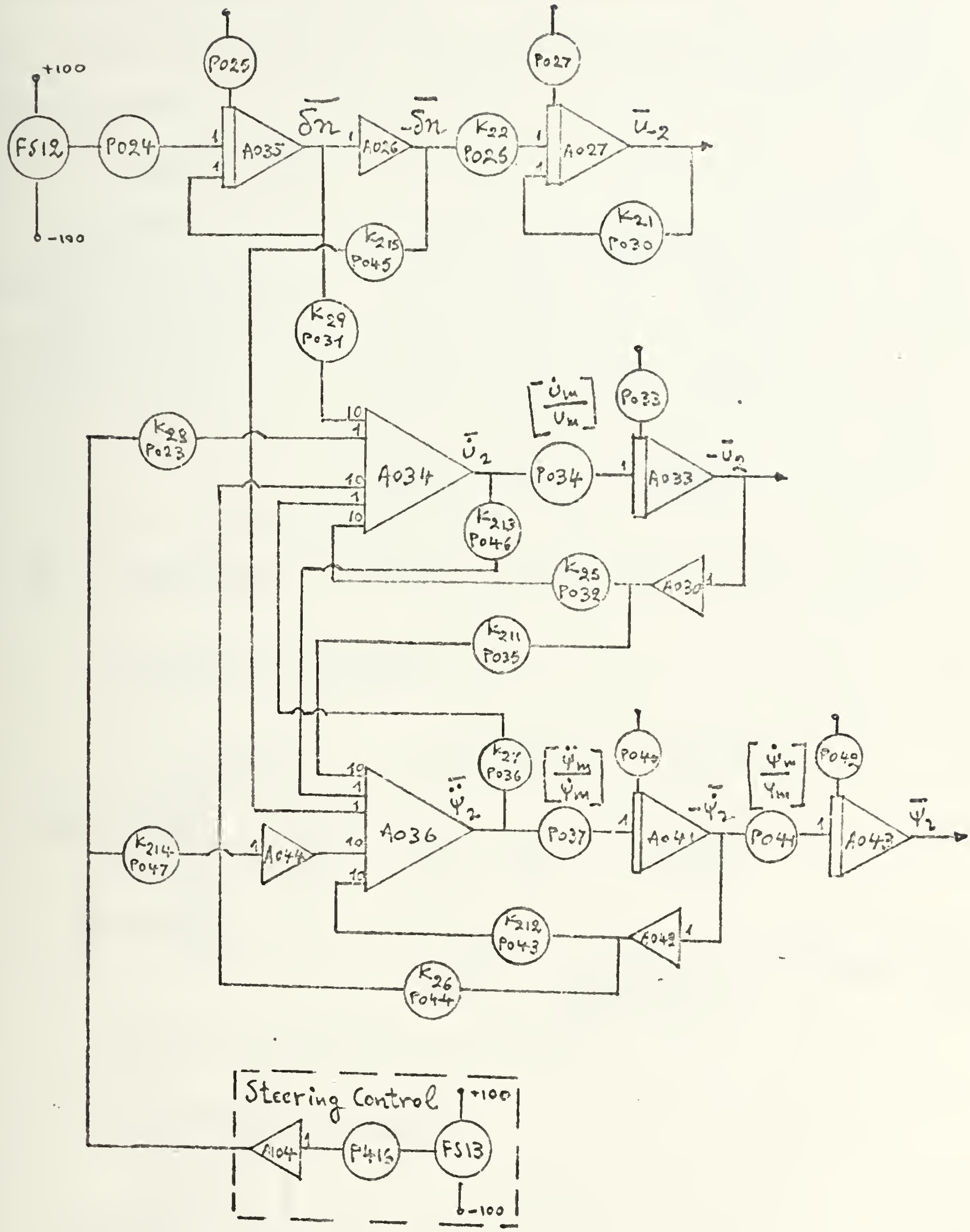
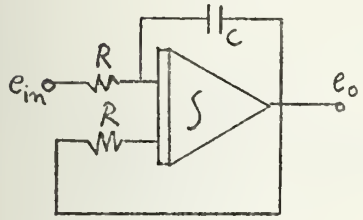


Figure 8. Analog diagram for study of dynamic behavior of ship No. 2.

The dynamic behavior of the ships separately is of interest. Also note that all the initial conditions were set equal to zero.

1. Dynamic Test



Amplifier A001–A026

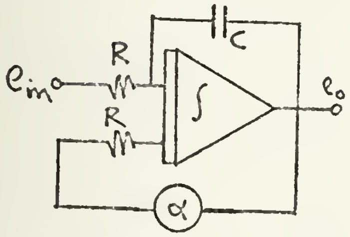
$$e_o = -[\frac{1}{RC_s} e_{in} - \frac{1}{RC_s} e_o]$$

$$|e_o| = \frac{1}{RC_s} e_{in} - \frac{1}{RC_s} e_o$$

$$\frac{e_o}{e_{in}} = \frac{1}{1+RC_s} = \frac{1/RC}{S+1/RC}$$

$\tau = \frac{1}{RC} = \frac{1}{(1M\Omega)(1\mu F)} = 1$ sec   Settling time $= T_s = 4$ sec

Amplifier A003–A027



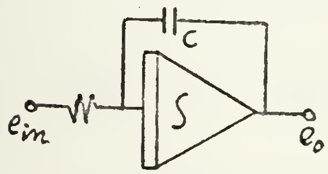
$$e_o = \frac{1}{RC_s} e_{in} - \frac{\alpha}{RC_s} e_o$$

$$\frac{e_o}{e_{in}} = \frac{1}{RC_s+\alpha} = \frac{1/RC}{S+\alpha/RC}$$

$$\tau = \frac{1}{\alpha/RC} = \frac{1}{\frac{0.0404}{(1M\Omega)(1\mu F)}} = \frac{1}{0.0404} \cong 24.8 \text{ sec}$$

Settling time $= T_s = 100$ sec

Amplifier A017–A043



$$e_o = -\frac{1}{RC_s}$$

$$\tau = \frac{1}{RC} = \frac{1}{(1M\Omega)(1\mu F)} = 1 \text{ sec}$$

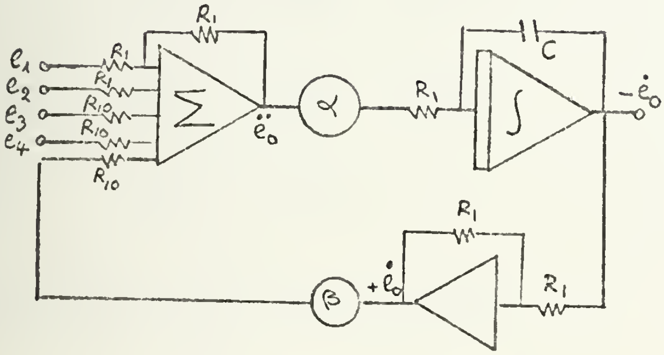
$$T_s = 4 \text{ sec}$$

Amplifier A013–A041

$$\ddot{e}_o = -[\frac{R_1}{R_1} e_1 + \frac{R_1}{R_1} e_2 + \frac{R_1}{R_{10}} e_3 + \frac{R_1}{R_{10}} e_4 + \frac{R_1}{R_1} \beta \frac{R_1}{R_{10}} \dot{e}_o]$$

$$-\dot{e}_o = -\frac{1}{R_1 C_s} \alpha \ddot{e}_o$$

$$\dot{e}_o = \frac{1}{R_1 C_s} \alpha \ddot{e}_o$$



where $R_1 = 1M\Omega$

$R_{10} = 0.1M\Omega$

$C = 1\mu F$

For the force free case it is:

$$e_1 = e_2 = e_3 = e_4 = 0$$

Hence:

$$\ddot{e}_o = 10\beta\, \dot{e}_o$$

and

$$\dot{e}_o = \frac{-1}{R_1 C} \int \alpha \ddot{e}_o \, dt$$

$$\ddot{e}_o = \frac{1}{R_1 C} \alpha \ddot{e}_o = -\frac{1}{R_1 C} 10\beta\alpha\, \ddot{e}_o$$

or

$$\ddot{e}_o + \frac{1}{R_1 C}(10\beta\alpha)\dot{e}_o = 0, \text{ let } x = \dot{e}_o \text{ then } \dot{x} = \ddot{e}_o$$

so $$\dot{x} + \frac{1}{R_1 C}(10\beta\alpha)x = 0$$

Thus the characteristic equation becomes

$$S + \frac{1}{R_1 C}(10\beta\alpha) = 0$$

Hence:

$$\tau = \frac{R_1 C}{10\alpha\beta} = \frac{1}{(10)(0.5607)(0.0250)} = \frac{100}{14} = 7.15 \text{ sec}$$

Thus:

$$T_s \cong 4 \times 7.15 = 28.6 \cong 30 \text{ sec}$$

By another way the same results can be obtained, i.e.

$$-\dot{e}_o = -\frac{\alpha}{R_1C} \int \ddot{e}_o \, dt$$

$$\dot{e}_o = \frac{\alpha}{R_1C} \int \ddot{e}_o \, dt$$

and

$$\ddot{e}_o = -10\beta\dot{e}_o$$

substituting this back gives:

$$\dot{e}_o = -\frac{\alpha}{R_1C} 10\beta \int \dot{e}_o \, dt$$

and

$$\dot{e}_o = -\frac{10\alpha\beta}{R_1C} \int \dot{e}_o \, dt$$

or

$$E_{(s)} = -\frac{10\alpha\beta}{R_1C} \frac{E(s)}{s}$$

Hence

$$E_{(s)} = 1 + \frac{10\alpha\beta}{R_1C_s} = \frac{sR_1C+10\alpha\beta}{sR_1C} = \frac{\frac{sR_1C}{10\alpha\beta} + 1}{\frac{sR_1C}{10\alpha\beta}}$$

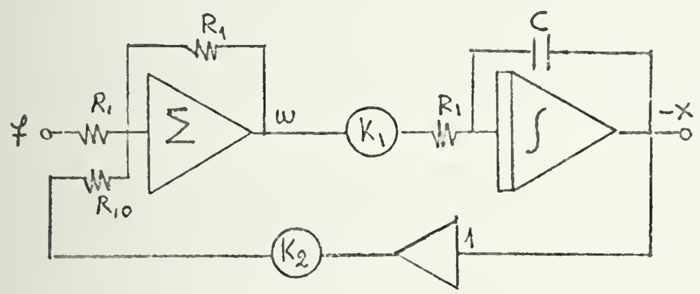
and

$$\tau = \frac{R_1C}{10\alpha\beta} = \frac{1\text{x}1}{(10)(0.5607)(0.0250)} = \frac{1}{0.14} = 7.15$$

$$\tau_s \cong 4 \times 7.15 \cong 30 \text{ sec}$$

Amplifier A005–A033

Again for the force free case only the closed loop is examined.



$$x = -\int k_1\, w dt$$

$$\dot{x} = -k_1 w$$

$$w = -[f + k_2 10x]$$

or for f=0: $w = -[k_2 10x]$

or $\dot{x} = -k_1 w = -k_1 [k_2 10x]$

$$\dot{x} + k_1 k_2 10x = 0$$

The characteristic equation is: $S+10k_1k_2 = 0$

$$\tau = \frac{1}{10k_1k_2} = \frac{1}{10(1.66\text{x}10^{-1})(2.379\text{x}10^{-1})} = \frac{1}{3.94\text{x}10^{-1}} = 2.5 \text{ sec}$$

$$T_s \cong 4 \times 2.5 = 10 \text{ sec}$$

Figure 9 shows next the response when approximately $\pm$ 5° of rudder angle is applied. Note that $\pm$ 1 computer unit corresponds to $\pm$ 20°. So a pot setting of P 437 for ship 1 and P416 for ship 2 equal to 1.0 corresponds to 20°. The sign of ΔR will be determined of course from the sign of the reference voltage. In fact for every curve taken by the chart the following relationship holds:

$$\frac{\pm 100}{x_m [\text{in units}]} = \frac{A[\text{divisions}] \times s[\text{volts/divisions}]}{x[\text{in units}]}$$

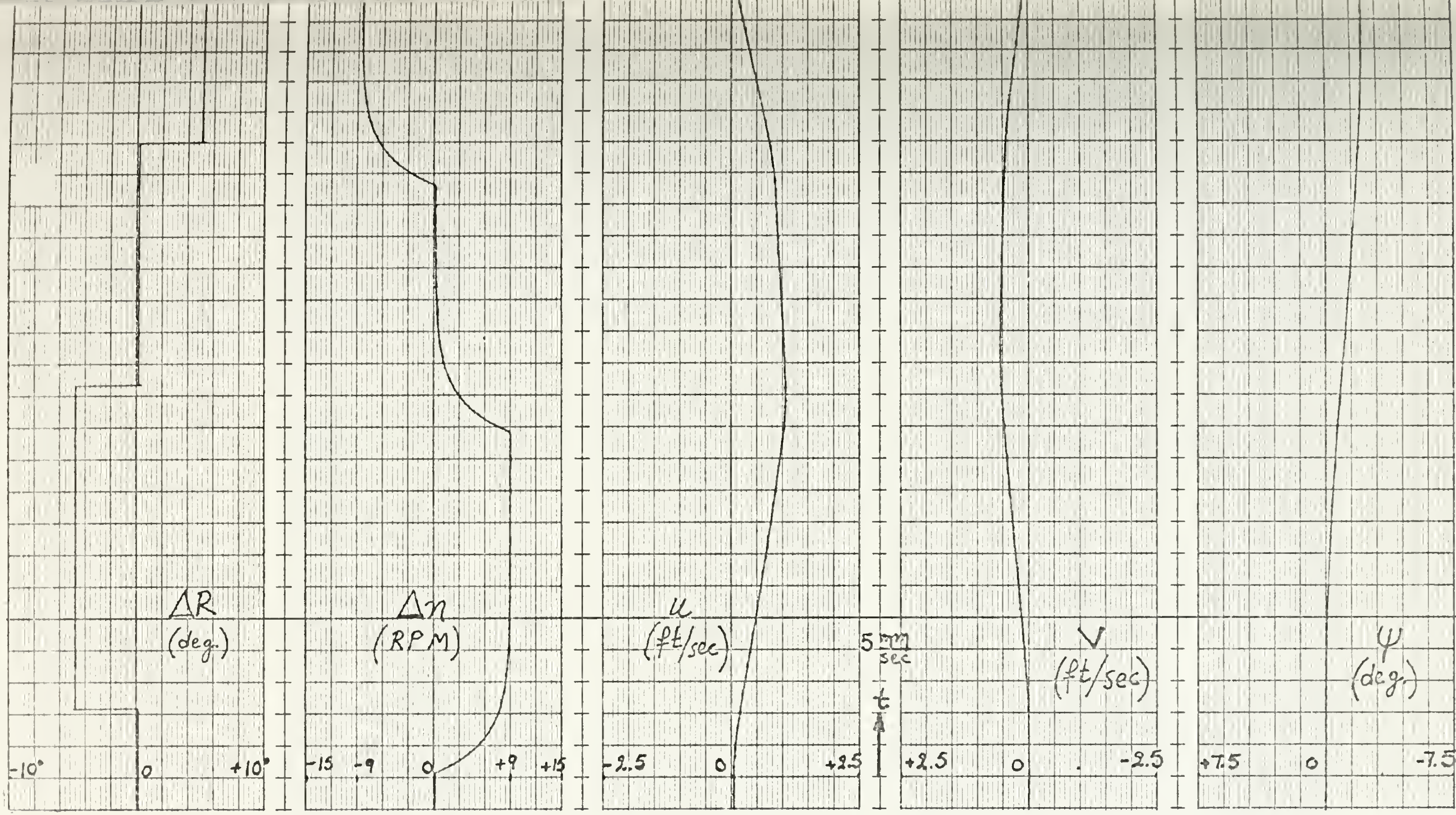


Figure 9a. Dynamic test of Mariner. $\Delta R = \pm 5°$

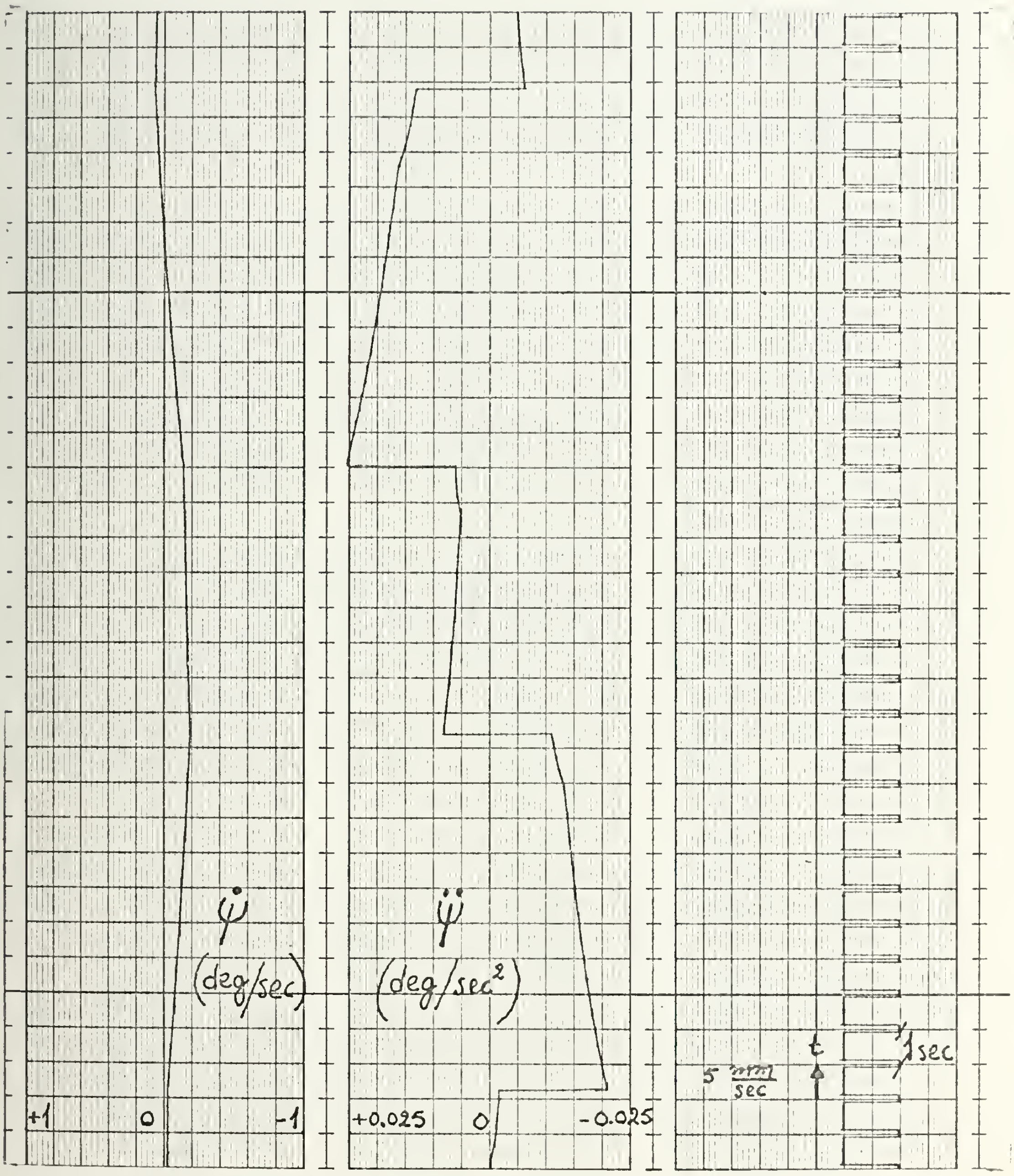


Figure 9b. Dynamic test of Mariner. $\Delta R = \pm 5°$

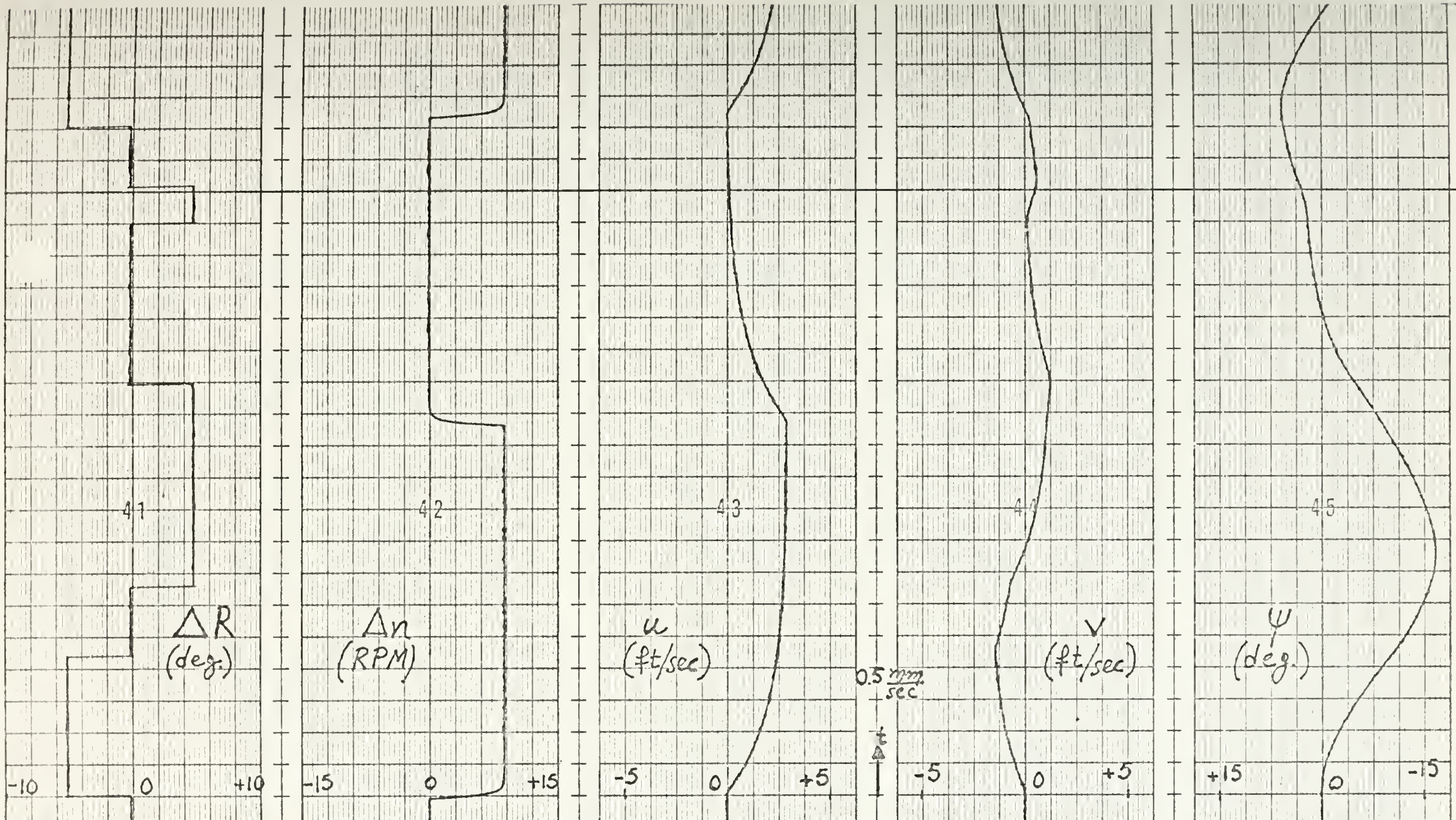


Figure 10a. Dynamic test of Mariner. $\Delta R = \pm 5°$

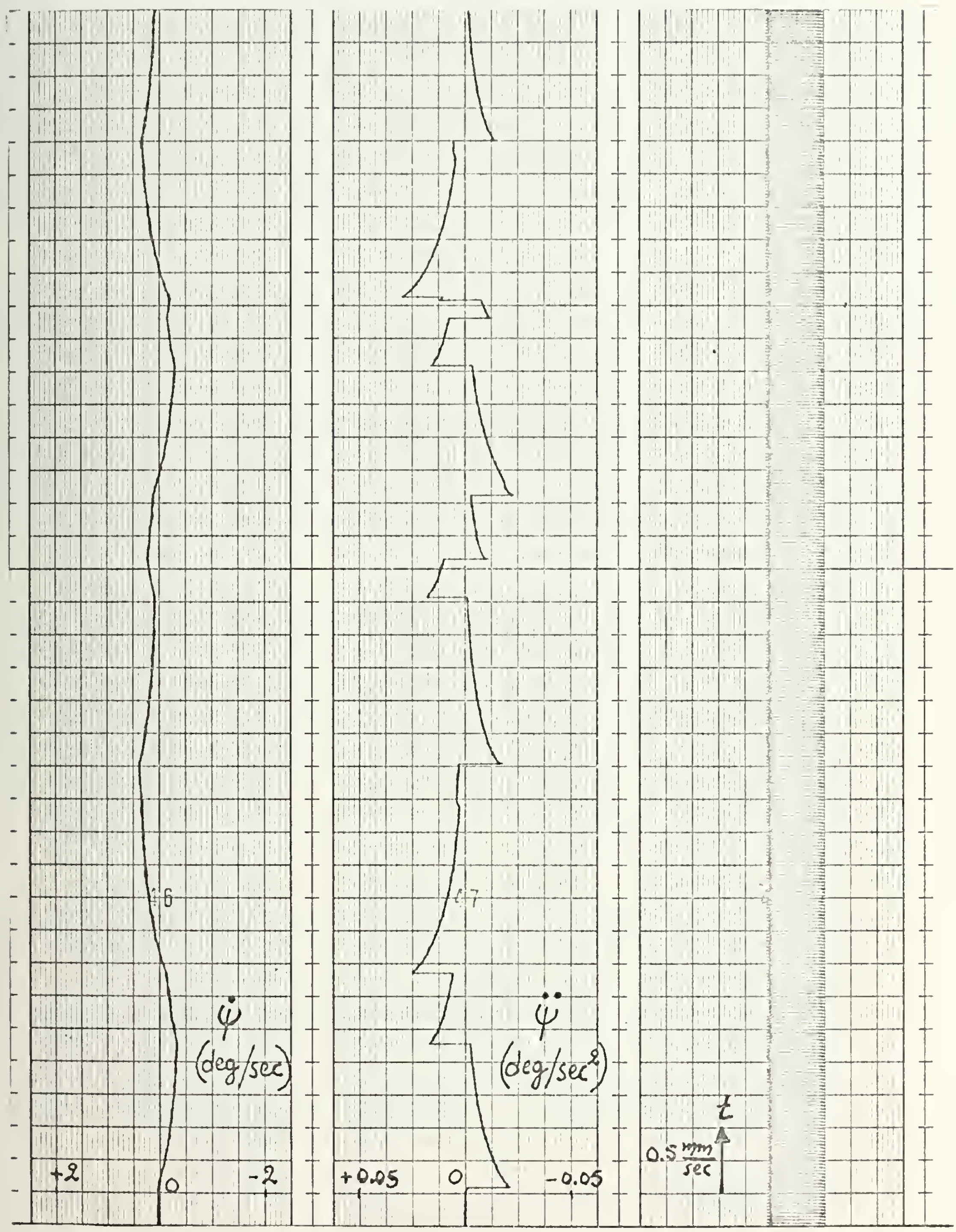


Figure 10b. Dynamic test of Mariner. $\Delta R = \pm 5°$

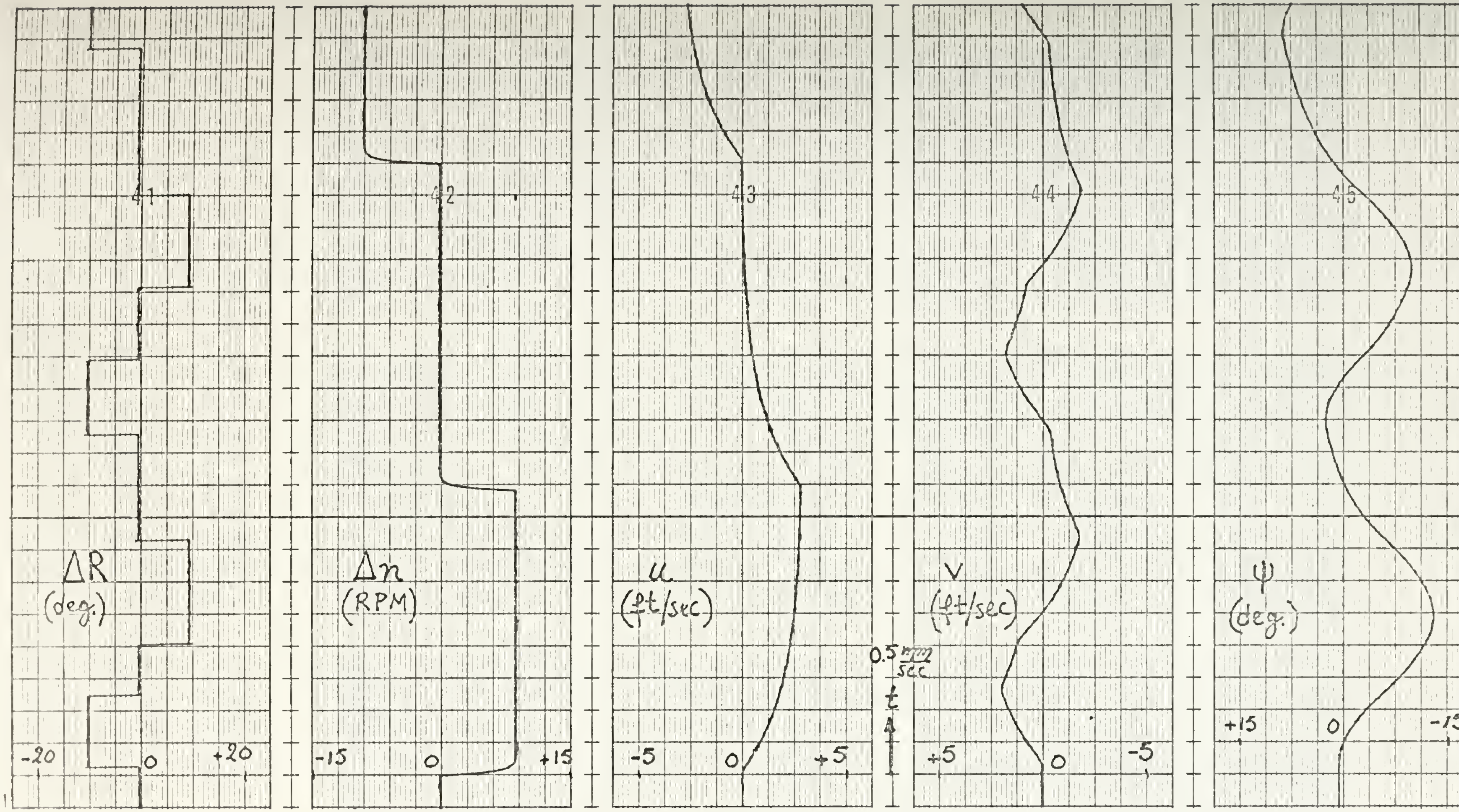


Figure 11a. Dynamic test of Mariner. $\Delta R = \pm 10°$

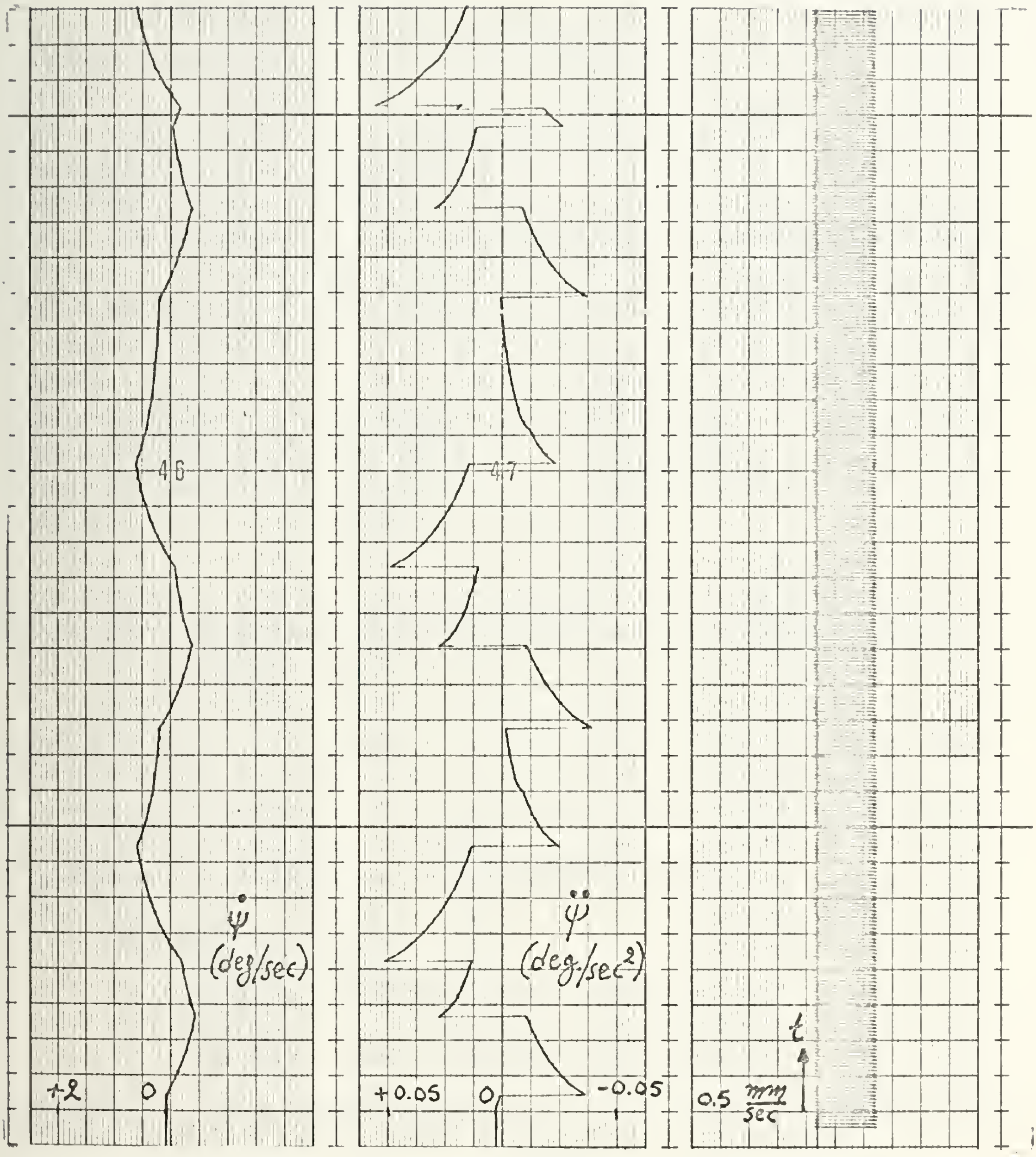


Figure 11b. Dynamic test of Mariner. $\Delta R = \pm 10°$

where: x_m = maximum expected value in actual units used in magnitude scaling the equation

A = divisions measured

s = sensitivity in volts/division

x = actual value of parameter x in actual units

100 volts = 1 computer unit

In Figure 10 the time scaling is changed and the linear response of Mariner is obtained in terms of $u, \psi, \dot{\psi}, \ddot{\psi}$

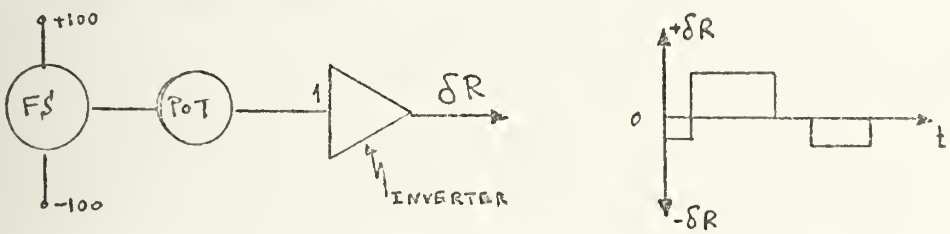


Figure 12. Steering Control used for the dynamic test of Mariner.

when $\Delta R = 15°$ is applied. In Figure 11 the response for $\Delta R = \pm 10°$ is shown. The time constants estimated previously are the same as the obtained ones.

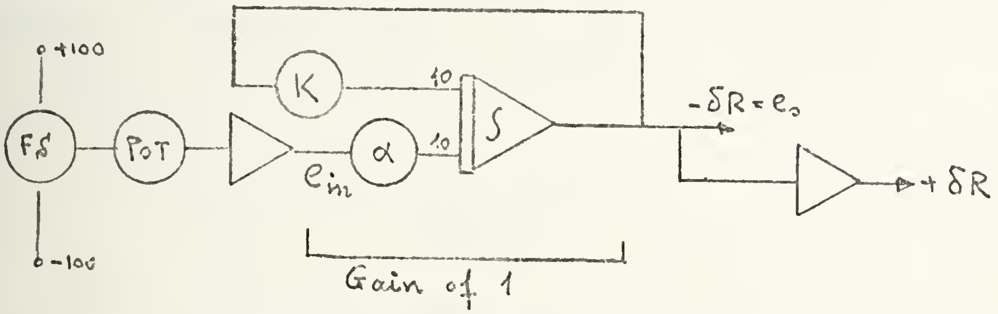
2. <u>Steering Control</u>

a. Analysis of Steering Control

Up till now a simplified model for the representation of the steering control was used, which produces step type commands + or − according to what reference voltage is chosen. The steering control configuration is shown in Figure 12.

One question which arises immediately after looking at Figure 12: is this a physically realizable steering control? The answer is no for several reasons.

Primarily the actual steering has a certain time lag in its response. Also for a given rudder change angle by the helmsman the actual rudder accelerates at the beginning



and then decelerates at the end of its final position. So to be closer to the physical situation of a steering control a definite time lag for the rudder action is needed as well as certain limits on the rate of change of the rudder angle, but without changing the initial gain set. The time lag can be produced by the above shown circuitry. The feed back gain is: $k = 0.175 \times 0.286 = 0.05$

The time constant and settling time are next calculated

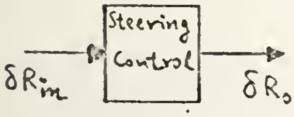
$$e_o = \frac{\alpha/10}{RC_s} e_{in} - \frac{k/10}{RC_s} e_o$$

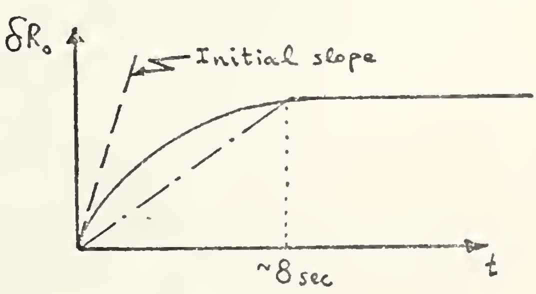
$$\frac{e_o}{e_{in}} = \frac{\alpha/10RC}{s+k/10RC}$$

$$k = 0.5$$

$$\tau = 1/[k/10RC] = 2 \text{ sec}$$

$$T_s \cong 4 \times 2 = 8 \text{ sec}$$





Now regarding the above shown diagram for the rudder the

following can be deduced. The desired time lag is obtained as well as the big initial slope of ΔR. The desired response is the dotted line curve ΔR_o seen in the previous sketch. To achieve that a limiter is used which limits the output e_1 as it can be seen from Figure 13a.

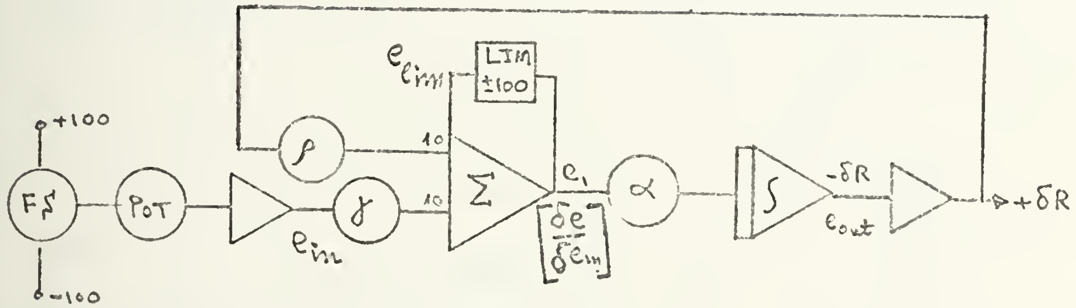
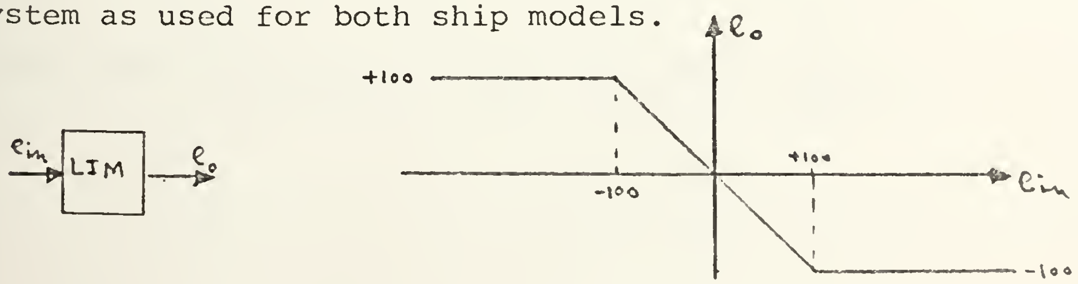
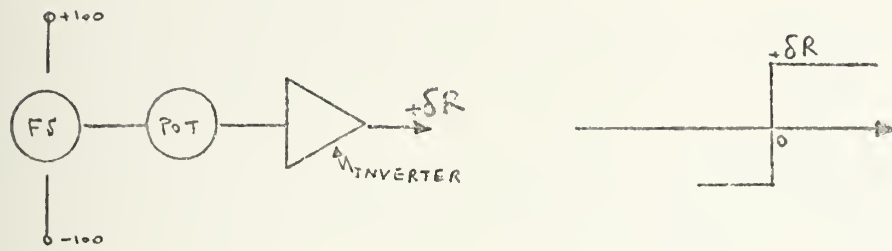


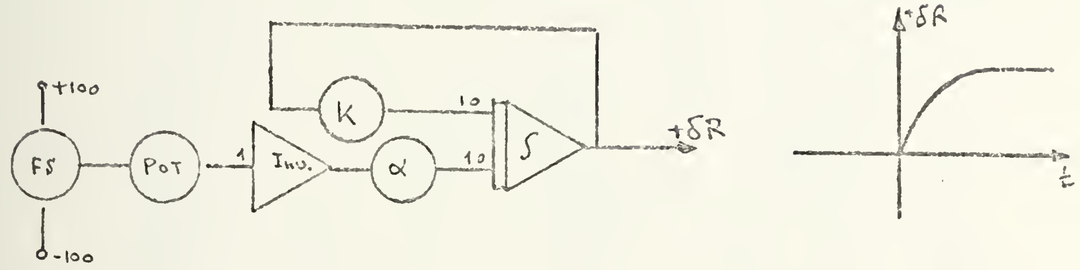
Figure 13a. Improved steering control.

The function of the limiter is similar to the saturation effect as next shown. Initially the error signal $[\delta e/\delta e_m]$ hits the $\pm$ 7° line which corresponds to +100 or −100 reference voltage, since the feedback is zero. Right after that due to the feedback the error signal is reduced almost linearly to zero. The time required for this is the desired time lag. Figure 13b illustrates the various steps made for the improvement of steering control in terms of the output rudder command. Figure 14 shows the complete analog configuration of the steering control system as used for both ship models.

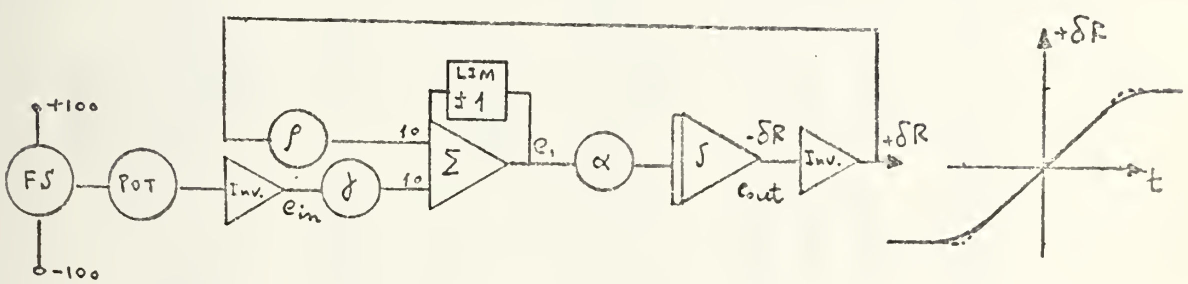




1. Step command output

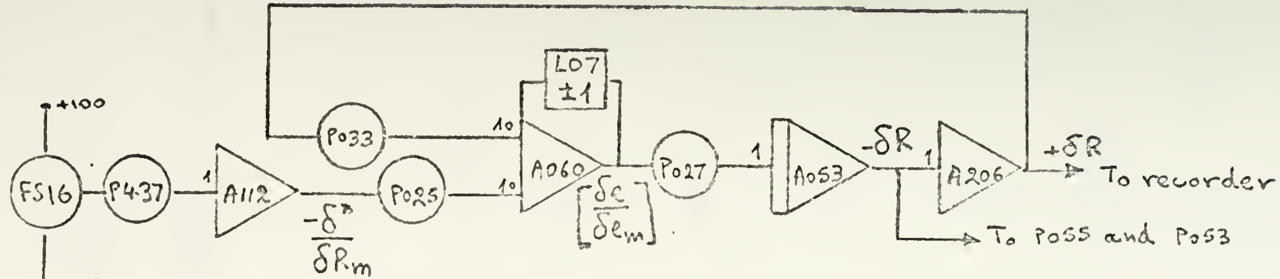


2. Command with time lag

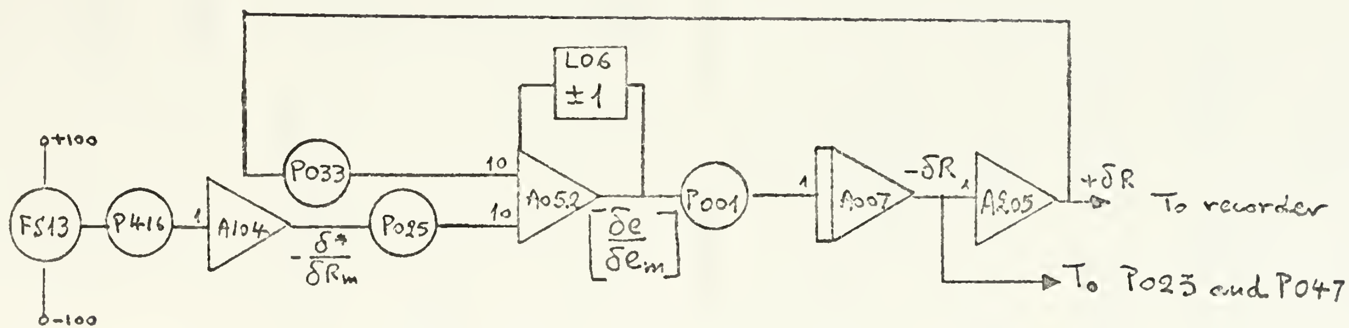


3. Command with both time lag and rate of change limitation

Figure 13b. Improvement steps of rudder commands.



Steering control for ship No 1



Steering control for ship No 2

where: $\delta R_m = 20°$, $P025 = P054 = P003 = P033 = \dfrac{\delta R_m}{10 \times \delta e_m} = 0.286$

$\delta e_m = 7°$

$K_m = 0.5$, $P001 = P027 = \dfrac{K \delta e_m}{\beta \delta R_m} = 0.175$, for real time $\beta = 1$

Figure 14. Steering control for ship No 1 and No 2.

b. Time Lag and Settling Time of Improved Steering Control

From Figure 13a it can be seen that:

$$e_{out} = -\int \alpha\, e_1\, dt$$

$$e_1 = e_{le_{im}} + \frac{\rho}{10} e_{out} + \frac{\gamma}{10} e_{in} \qquad \text{where}$$

$$|e_{le_{im}}| = 100, \; -100 \leq e_1 \leq +100$$

$$e_{out} = -\int \alpha \left[e_{le_{im}} + \frac{\rho}{10} e_{out} + \frac{\gamma}{10} e_{in}\right] dt$$

For the force free case and within the specified limits it is:

$$e_{out} = -\int \alpha \frac{\rho}{10} e_{out}\, dt$$

$$\dot{e}_{out} = -\alpha \frac{\rho}{10} e_{out}$$

$$\text{or} \qquad \dot{e}_{out} + \alpha \frac{\rho}{10} e_{out} = 0$$

The characteristic equation is:

$$s + \frac{\alpha\rho}{10} = 0$$

$$\text{and} \qquad \tau = 1 / [\alpha\rho/10]$$

Now for: $\delta R_m = 20°$

$\delta e_m = 7°$

$k = 0.5$

$\beta = 1$ for real time simulation and

from $\rho = \gamma = \dfrac{\delta R_m}{10\delta e_m} = 0.286$

$$\alpha \doteq \frac{k\delta e_m}{\delta R_m} = 0.1750$$

it is obtained: $\tau = 2$ sec

and $T_s \cong 8$ sec as before.

Figure 15a and 15b show the responses for input commands $\Delta R = + 5°$ and $\Delta n = \pm 9$ RPM but with different time scaling respectively. Figure 16a and 16b show the responses for input commands $\Delta R = \pm 10°$ and $\Delta n = \pm 9$ RPM but again with different time scaling of the chart recorder. It is observed that the expected time constants and settling times can be measured.

C. TRANSFORMATION OF COORDINATES

1. Introductory Discussion

The responses observed in the previous sections were taken with respect to the Eulerian system, i.e. moving coordinate axes on the ship. This makes difficult the measurement of the separation distance between the two ships during the UNREP operation. It is desired therefore to use the space coordinate system, which for ease of computer print out is made to move ahead at 15 knots. It is also noted that the ship initially moves straight ahead at 15 knots. Figure 17 illustrates the above discussion.

From the inspection of Figure 17, equations (V-2) can be recalled, i.e.

$$\dot{x}_o = u \cos \psi - u \sin \psi$$

$$\dot{y}_o = u \sin \psi + u \cos \psi$$

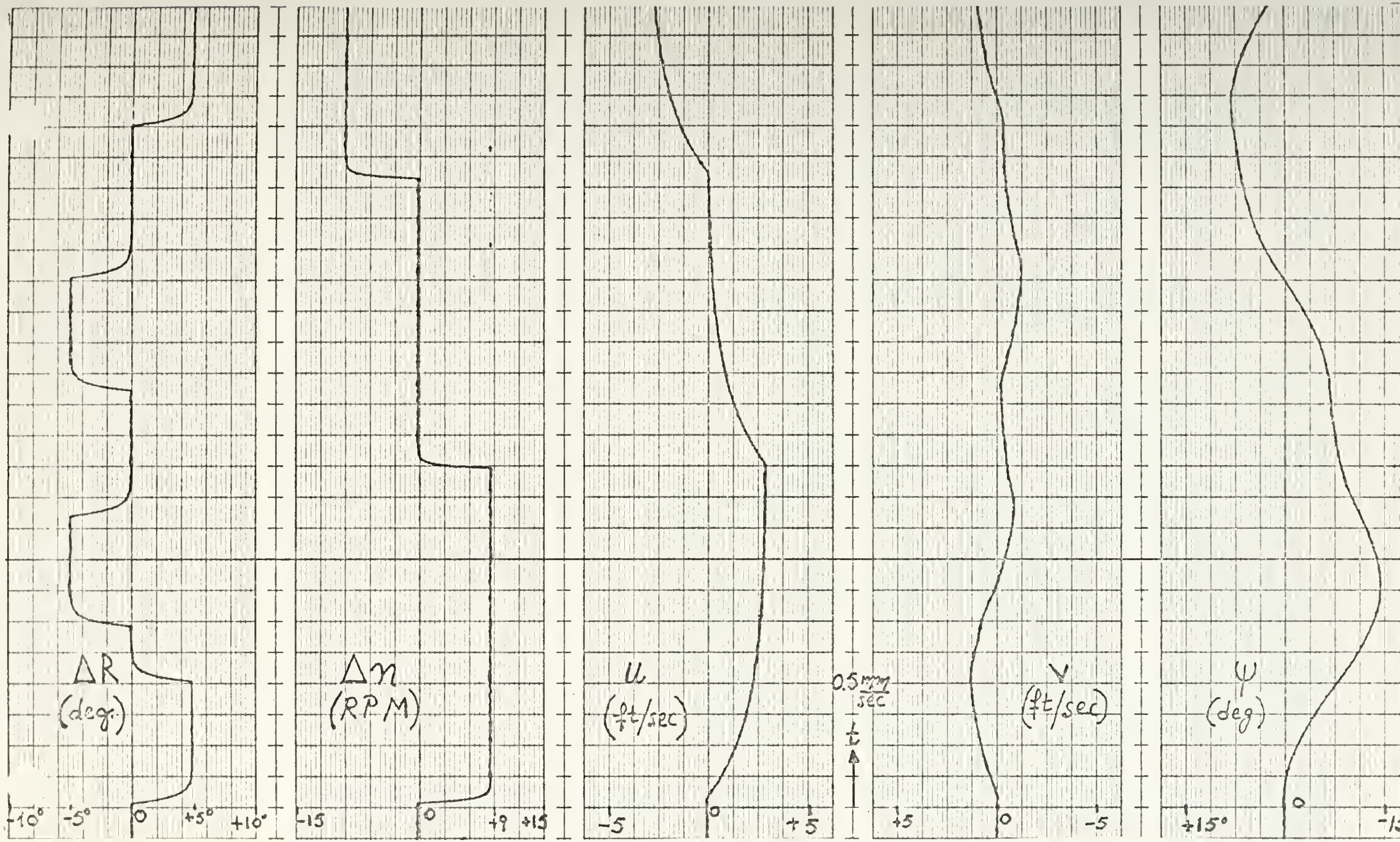


Figure 15a-1. Dynamic test of Mariner. ΔR = ± 5° , Δn = ± 9 RPM.

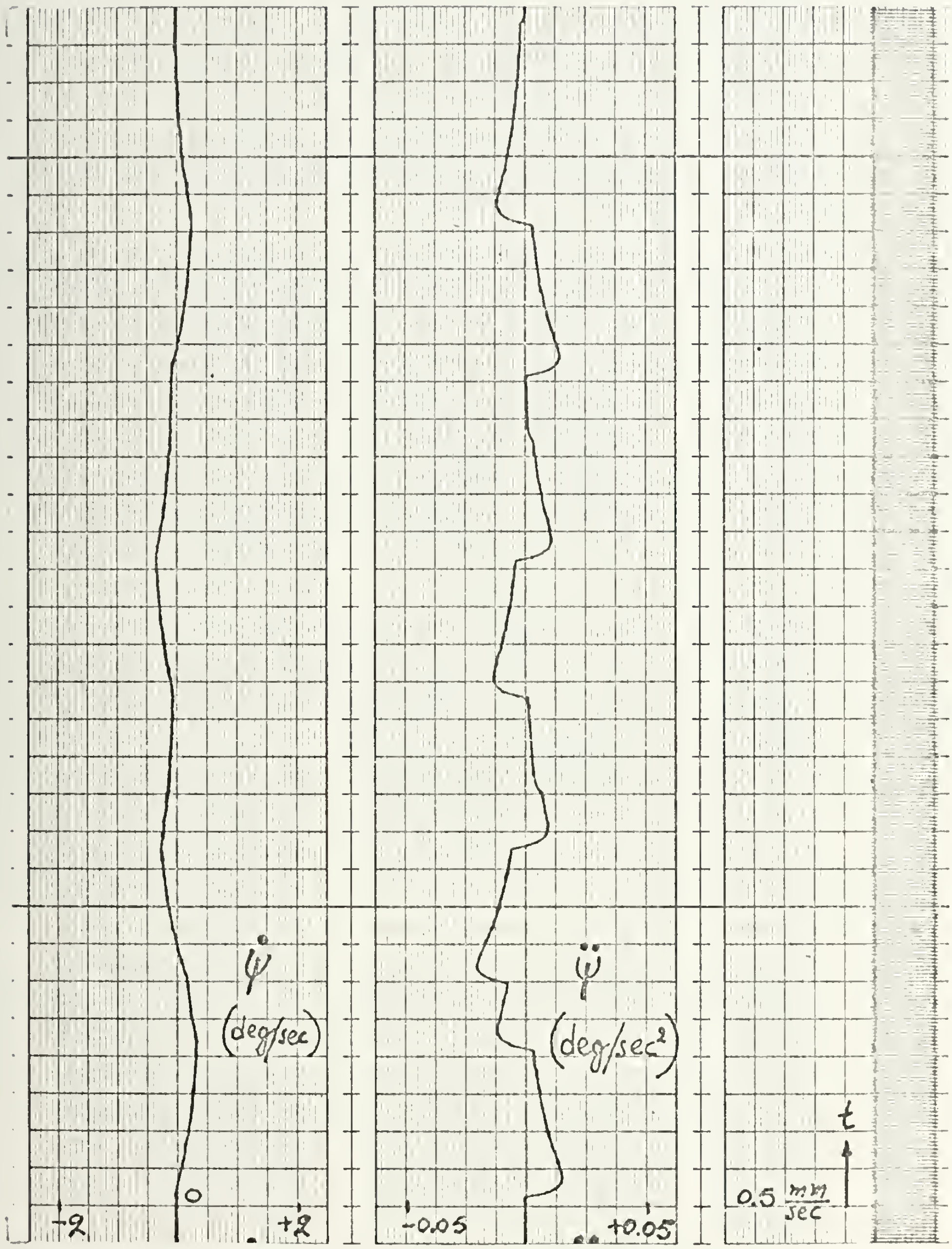


Figure 15a–2. Dynamic test of Mariner. $\Delta R = \pm 5°$, $\Delta n = 9$ RPM.

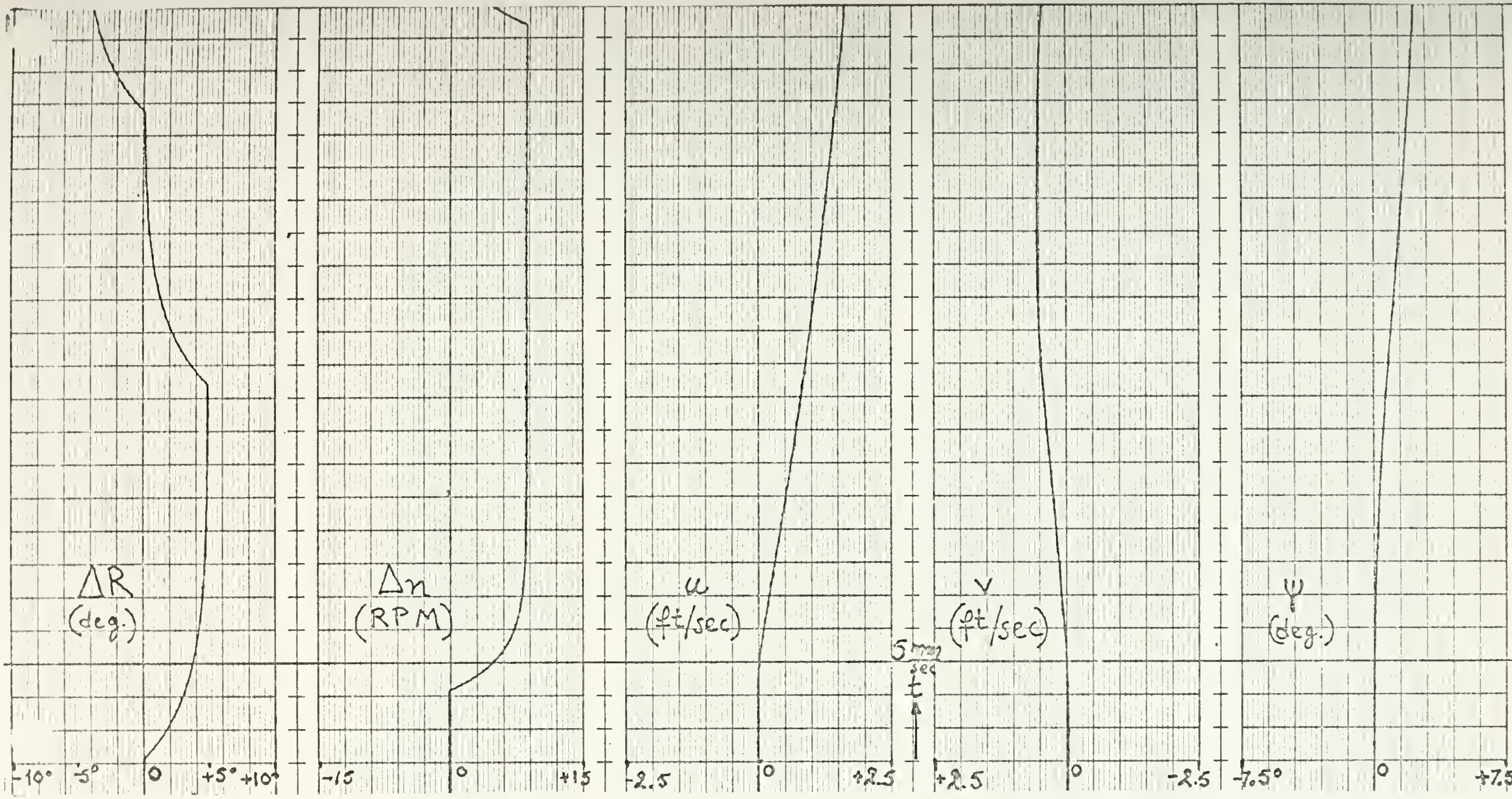


Figure 15b—1. Dynamic test of Mariner. $\Delta R = \pm 5°$, $\Delta n = \pm 9$ RPM.

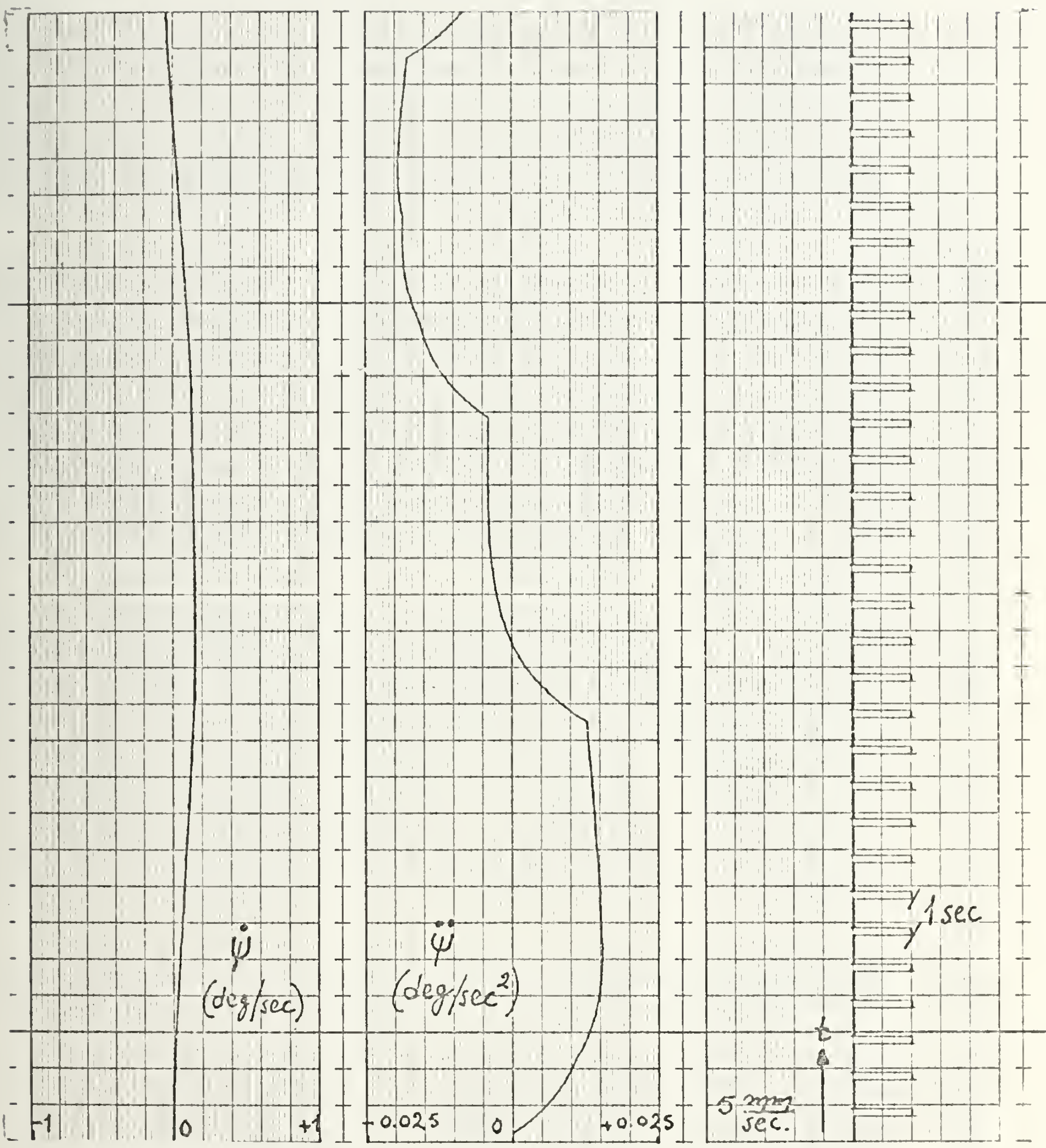


Figure 15b–2. Dynamic test of Mariner. $\Delta R = \pm 5°$, $\Delta n = \pm 9$ RPM.

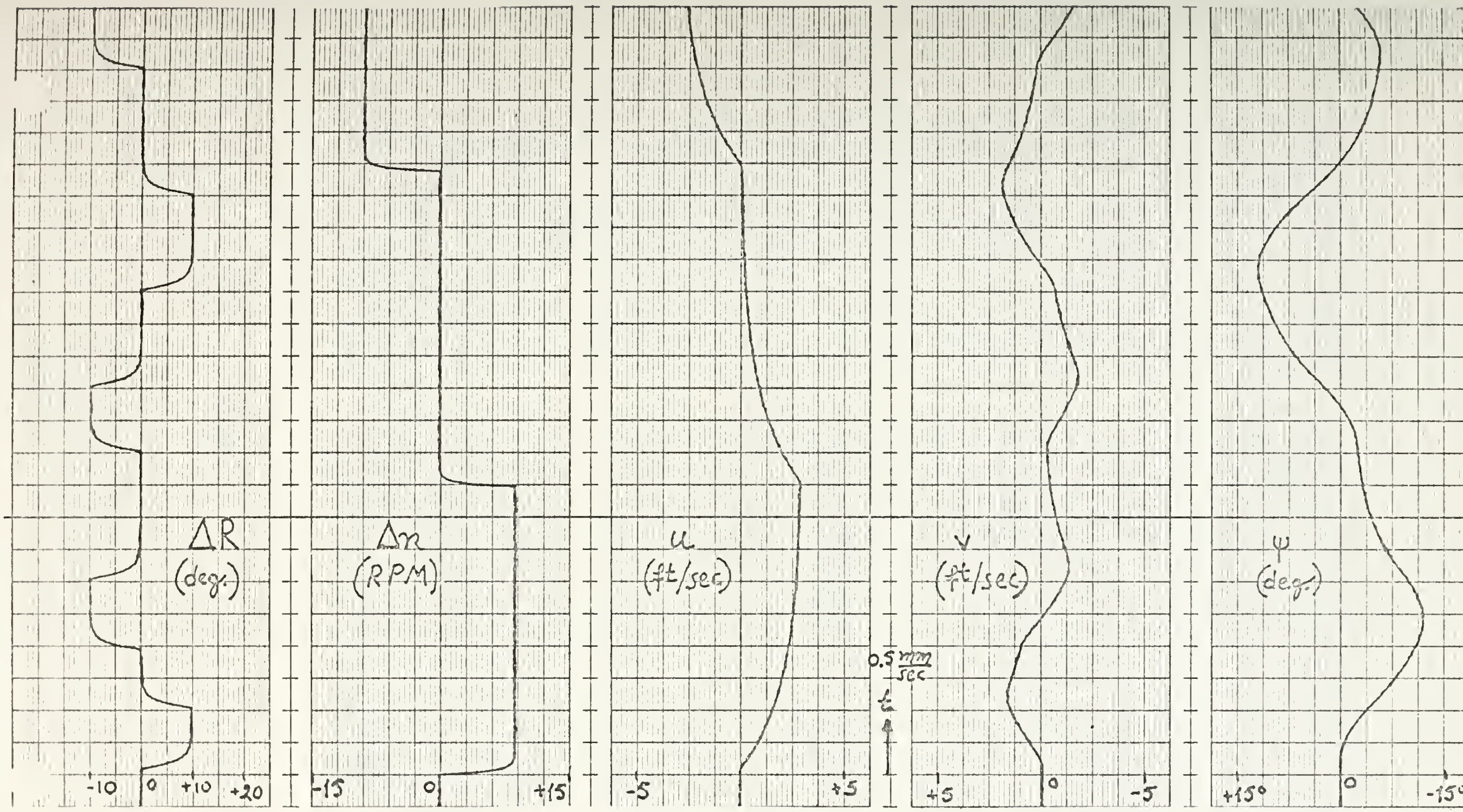


Figure 16a-1. Dynamic test of Mariner. $\Delta R = \pm 10°$, $\Delta n = \pm 9$ RPM.

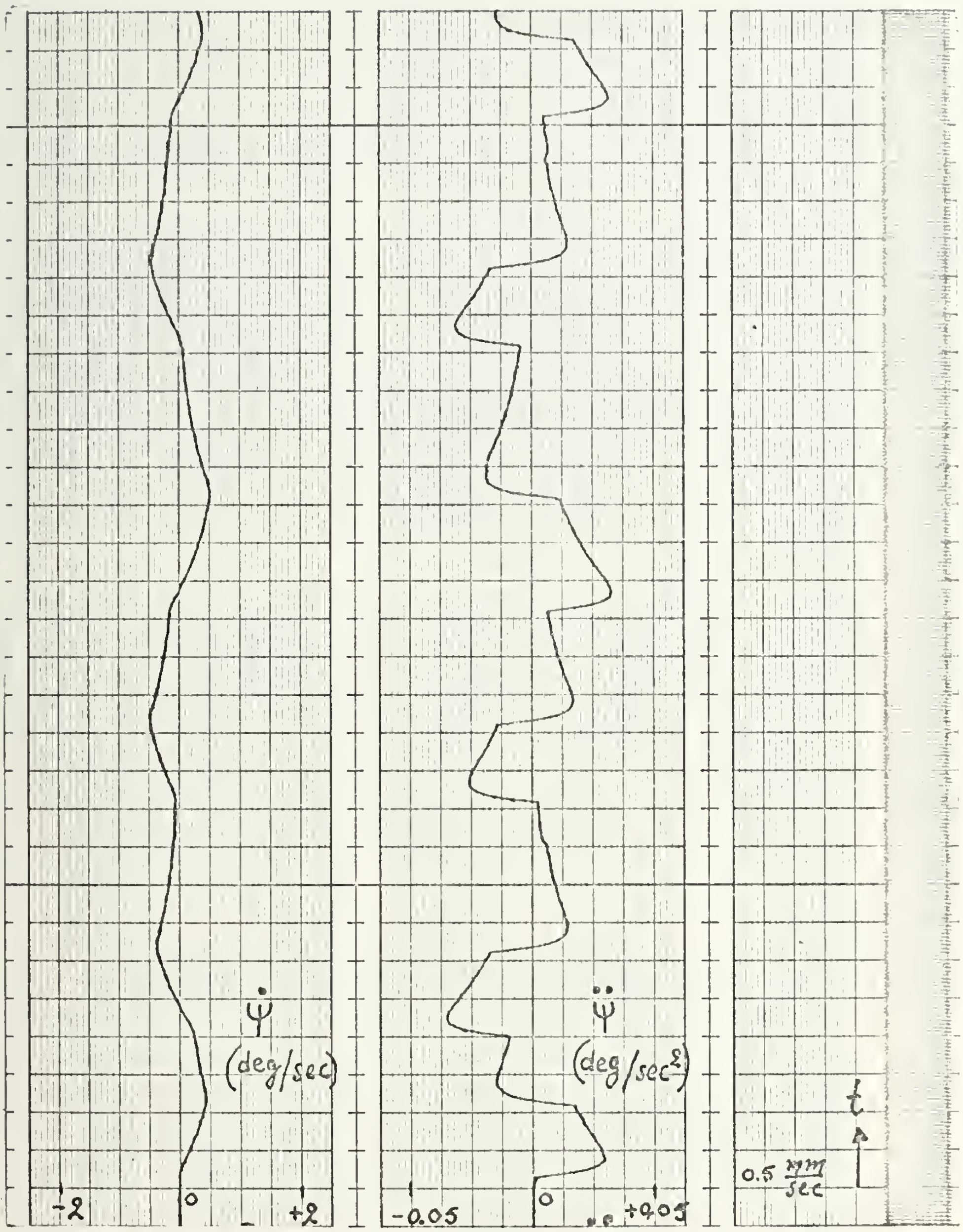


Figure 16a–2. Dynamic test of Mariner. $\Delta R = \pm 10°$, $\Delta n = \pm 9$ RPM.

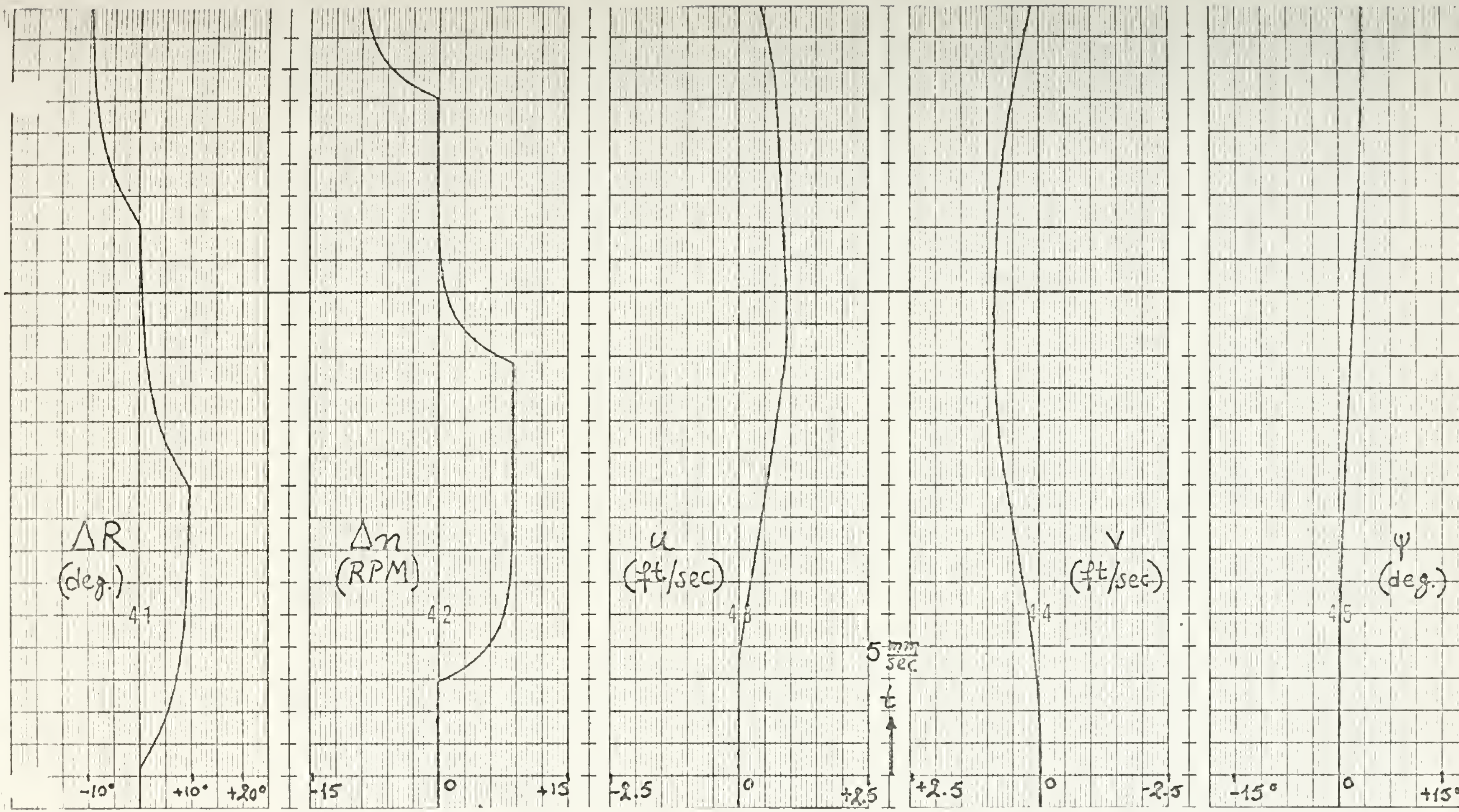


Figure 16b—1. Dynamic test of Mariner. $\Delta R = \pm 10°$, $\Delta n = \pm 9$ RPM.

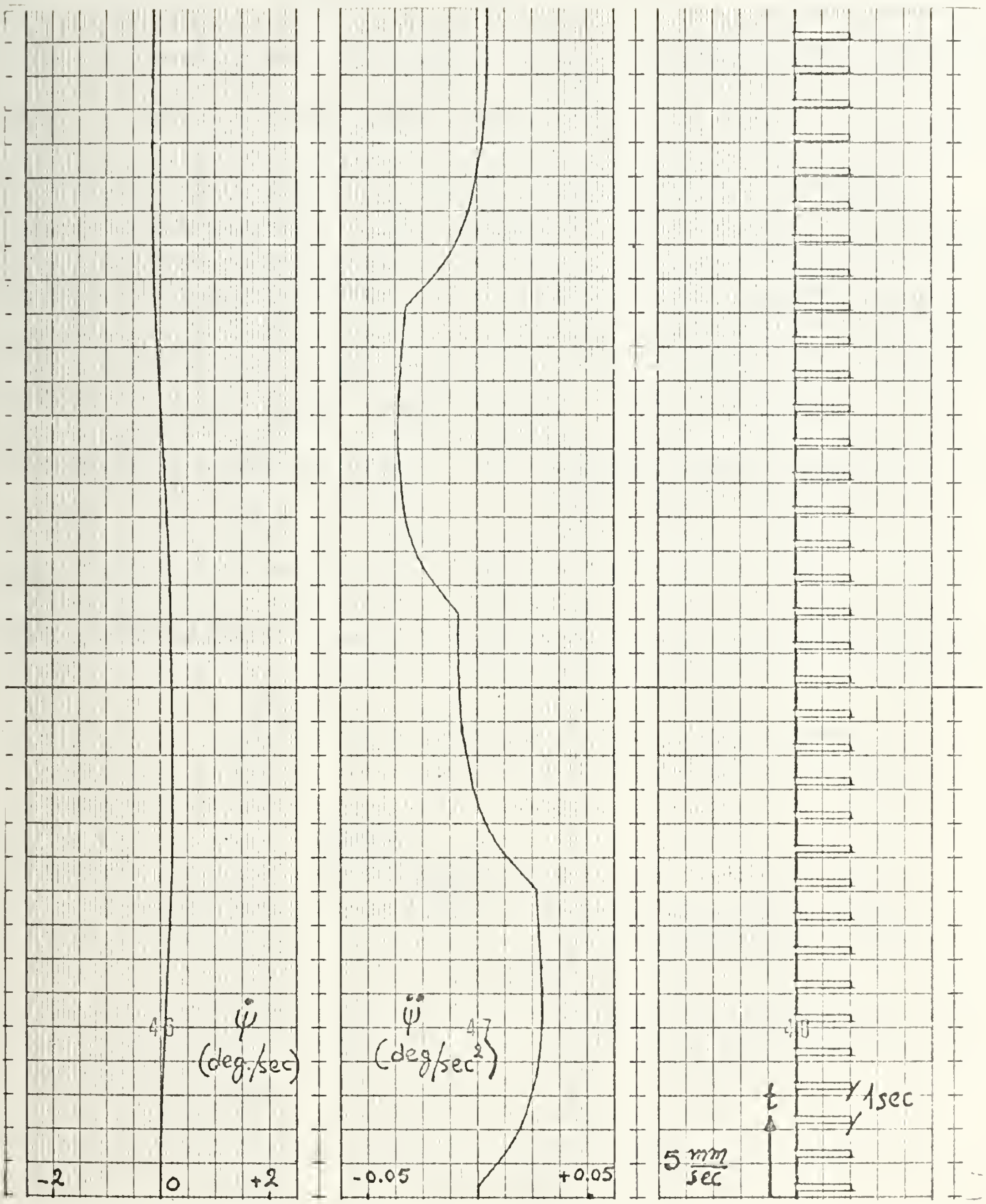


Figure 16b–2. Dynamic test of Mariner. $\Delta R = \pm 10°$, $\Delta n = \pm 9$ RPM.

At this point computer unit XDS-9300 is used in hybrid operation, needed for the coordinates transformation, with the analog unit CI-5000. Computer program IVA and IVB show the source decks used and Figure 18a shows the control statements used for both digital and analog computers. Figure 18b shows the communications trunk lines used between digital and analog computers. Figures 19a and 19b show the analog patching diagrams used for the coordinates transformation for both ships respectively. Table X contains the potentiometer values used. It should be mentioned here that for the control of the hybrid operation for ship No 1 the logic switches "0" and "1" were used. For ship No 2 the logic switches "2" and "3" were used. The hybrid operation

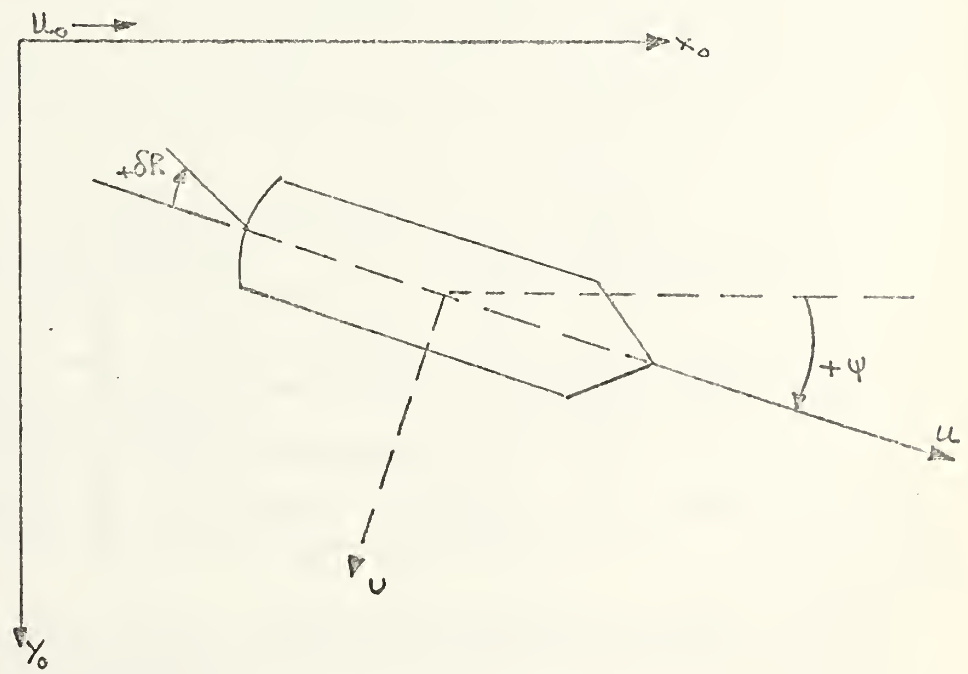


Figure 17. Space coordinates system

was performed with both the switches being in the middle position.

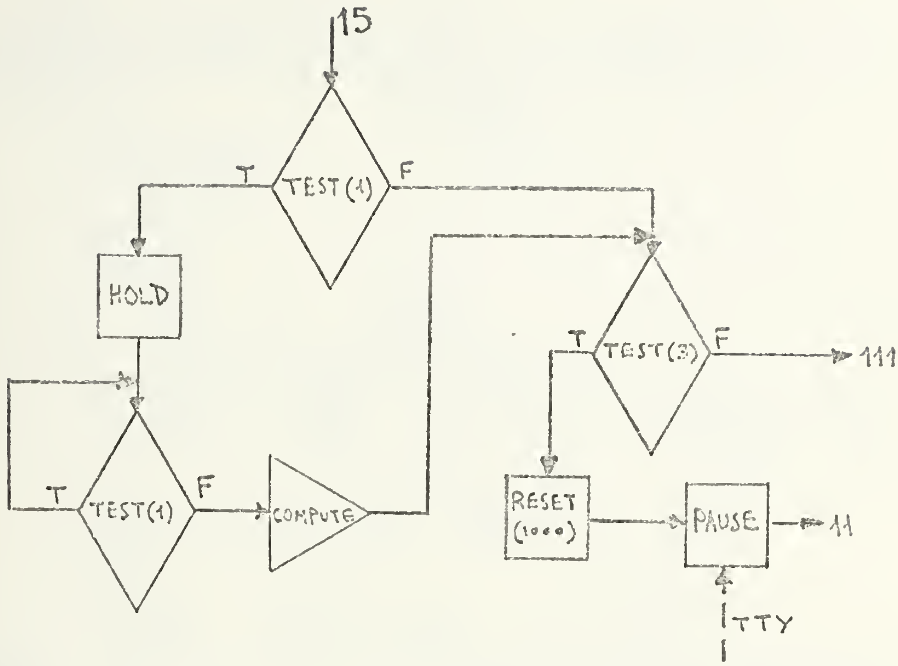


Figure 18a. Flow chart for control of analog and digital unit.

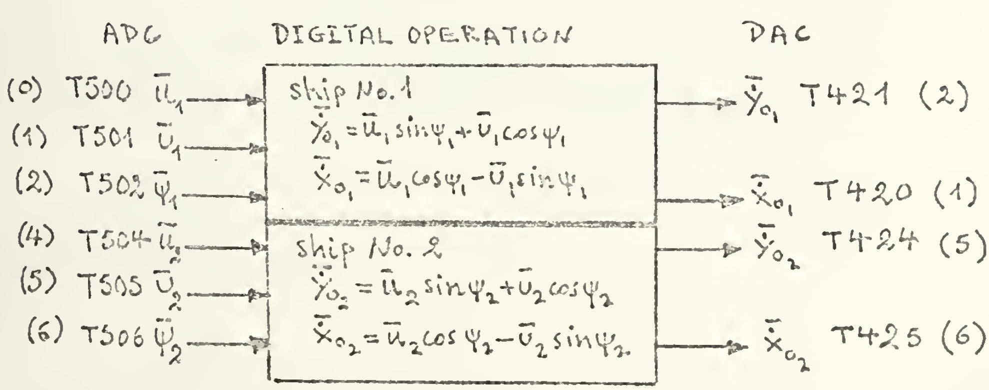
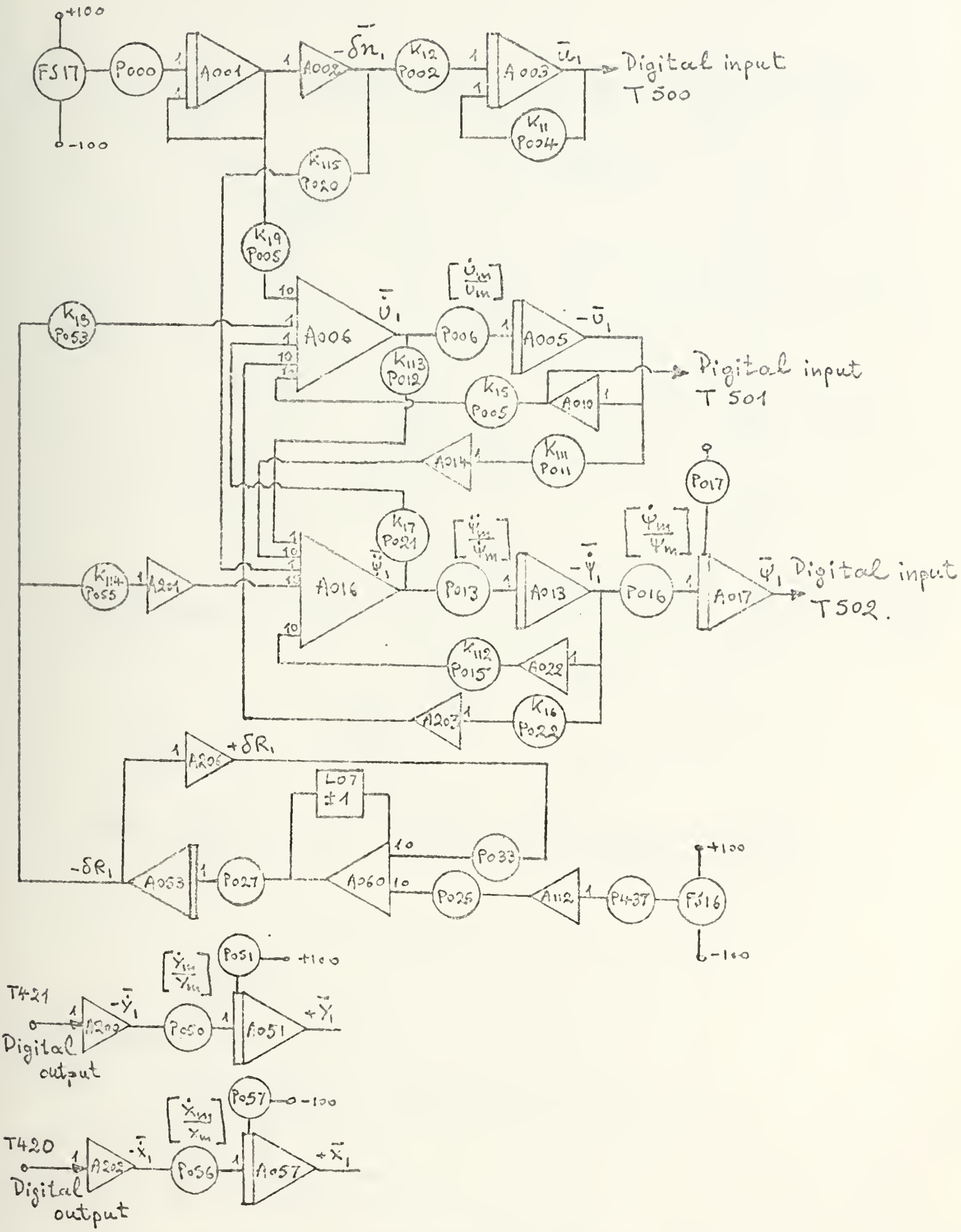
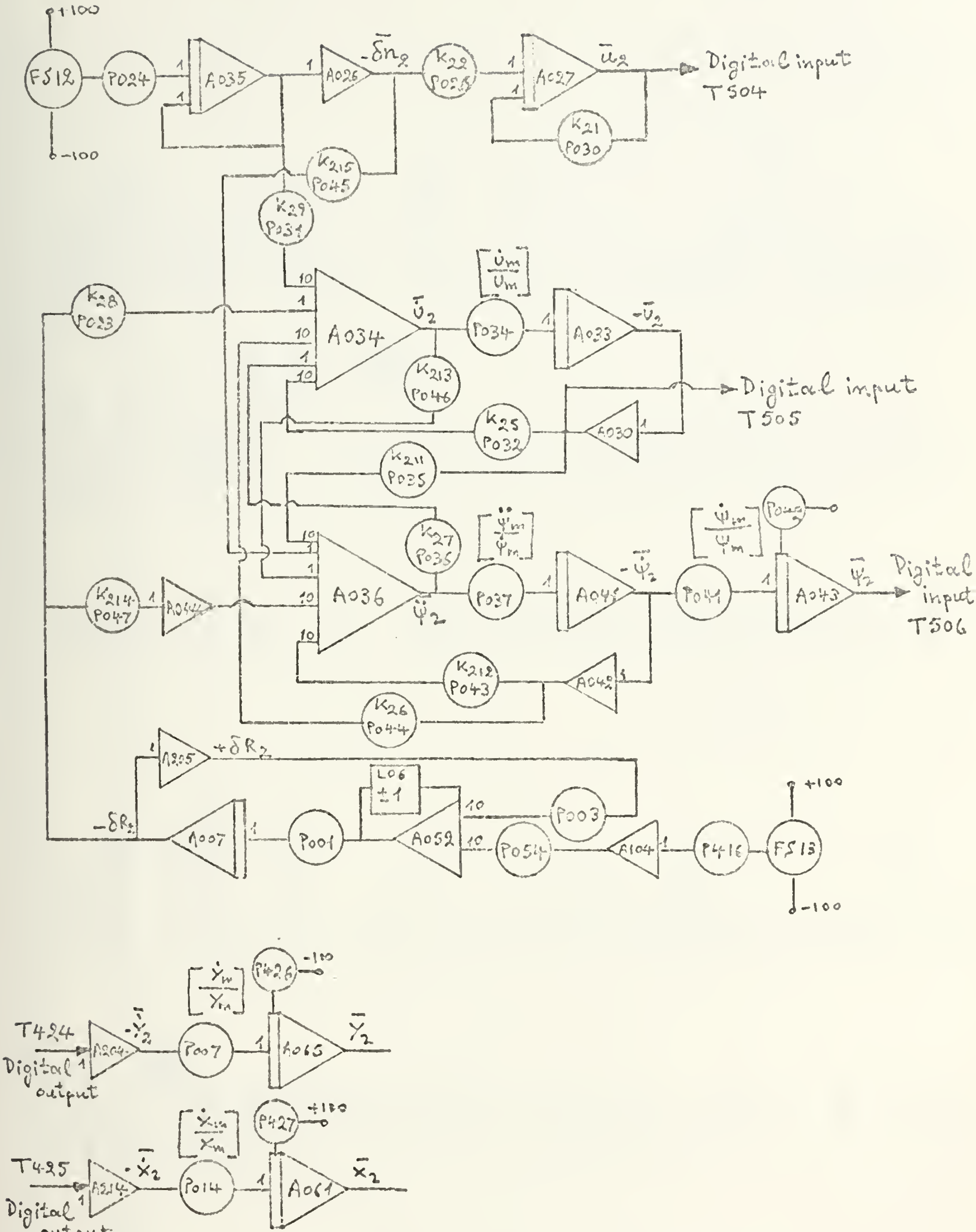


Figure 18b. Communication trunk lines between digital and analog computer used for the coordinates transformation.



(After coordinates transformation section)

Figure 19a. Analog diagram used for hybrid simulation for ship No. 1.



(After coordinates transformation section)

Figure 19b. Analog diagram used for hybrid simulation for ship No 2.

TABLE X

POTENTIOMETER VALUES FOR COORDINATES TRANSFORMATION

Pot Address	Ship No 1 Assigned Value	Corres-ponded Parameter	Pot Address	Ship No 2 Assigned Value	Corres-ponded Parameter
	0.3= 9RPM		P051	0.3=48ft	y_m=160ft
P000	0.5=15RPM	FS-17(δn)		0.25=40 ft	IC-A051
P025	0.2860	$\delta R_m/[10\delta e_m]$	P056	0.0092	$\dot{x}_m/x_m$
P002	0.0803	K_{12}	P057	0.454=250ft	x_m=550 ft
P033	0.2860	$\delta R_m/[10\delta e_m]$		0.4 = 225ft	IC-A057
P004	0.0404	K_{11}	P437	0.5 = 10°ΔR	ΔR_m = 20°
P005	0.0052	K_{19}		0.25= 5° ΔR	FS-16
				0.3 = 9RPM	
P006	0.1660	$\dot{u}_m/u_m$	P024	0.5 = 15RPM	FS-12(δn)
P010	0.2379	K_{15}	P054	0.2860	$\delta R_m[10\delta e_m]$
P011	0.2383	K_{111}	P026	0.0803	K_{22}
P012	0.4717	K_{113}	P001	0.1750	$k\ e_m/\ R_m$
P013	0.0250	$\psi_m/\dot{\psi}_m$	P030	0.0404	K_{21}
P015	0.5607	K_{112}	P045	0.0920	K_{215}
P016	0.1340	$\dot{\psi}_m/\psi_m$	P031	0.0052	K_{29}
P017	0.00	IC-A017	P023	0.0905	K_{28}
P020	0.0920	K_{115}	P034	0.1660	$\dot{u}_m/u_m$
P021	0.0097	K_{17}	P003	0.2860	$R_m/[10\ e_m]$
P022	0.3576	K_{16}	P046	0.4717	K_{213}
P053	0.0905	K_{18}	P032	0.2379	K_{25}
P027	0.1750	$k\delta e_m \vert \delta R_m$	P035	0.2383	K_{211}
P055	0.1497	K_{114}	P047	0.1497	K_{214}
P050	0.0337	$\dot{y}_m/y_m$			

TABLE X (continued)

P036	0.0097	K_{27}
P037	0.0250	$\ddot{\psi}_m/\dot{\psi}_m$
P041	0.1340	$\dot{\psi}_m/\psi_m$
P042	0.00	IC—A043
P043	0.5607	K_{212}
P044	0.3576	K_{26}
P007	0.0337	$\dot{y}_m/y_m$
	0.3=48ft	y_m = 160ft
P426	0.25=40ft	IC—A065
P014	0.0092	$\dot{x}_m/x_m$
	0.454=250ft	x_m= 550ft
P427	0.40=225 ft	IC—A061
	0.5= 10°ΔR	ΔR_m = 20°
P416	0.25= 5°ΔR	FS—13

2. <u>Computed Linear Response of Mariner after Coordinates Transformation</u>

Figure 20 shows the linear response of the Mariner to approximately $\pm$ 10° changes referred to midships in the rudder angle.

Initially the Mariner is moving straight ahead at 15 knots with the rudder at midships ($\delta=0$), and then $\Delta R = \pm 10°$ is applied for 25 seconds. Three phases are observed for a turn.

a. Initial Approach Phase in which

$\dot{v}=0, \quad \dot{r}=\ddot{\psi}=0, \quad v=0, \quad r=\dot{\psi}=0, \quad \psi=0$

b. First Phase in which

$\dot{r}>0, \quad \dot{r}=\ddot{\psi}<0, \quad v=0, \quad r=\dot{\psi}=0$

This phase starts at the instant the rudder is turned, and ends before the rudder reaches its full deflection angle. The rudder force ($Y_\delta\delta$) and rudder moment ($N_\delta\delta$) are dominant and produce accelerations which are opposed only by the inertia of the Mariner.

It should be noted here that the rudder force $Y_\delta\delta$ is towards starboard, since the rudder is at the stern of the Mariner, which corresponds to a port (negative) turn although the transverse velocity v is positive (towards starboard).

c. Second Phase in which

$\dot{v}>0, \quad v>0, \quad \dot{r}=\ddot{\psi}<0, \quad r=\dot{\psi}<0$

It must be mentioned here that a force $Y_v v$ is created towards the center of the turn (towards port)

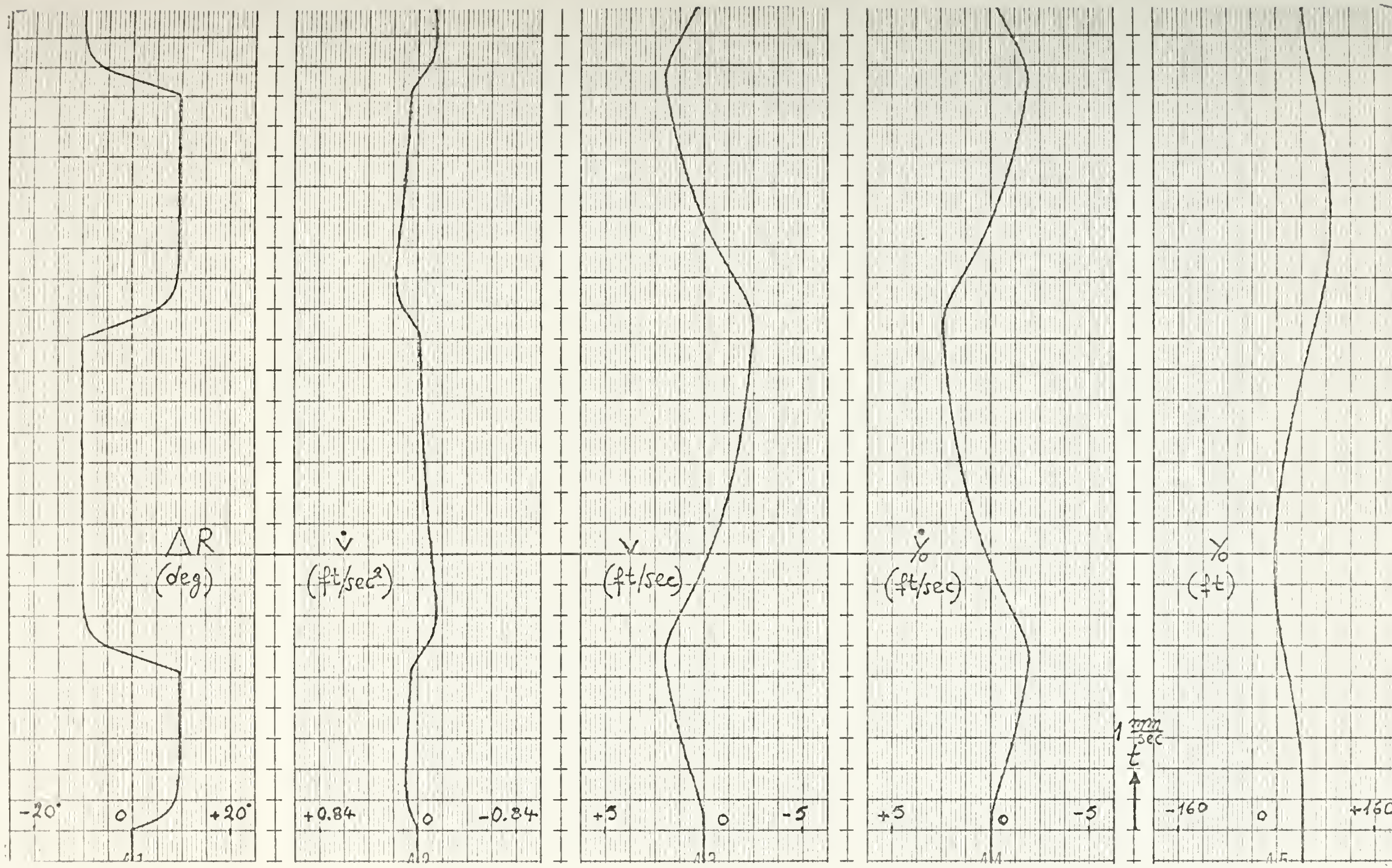


Figure 20–1. Characteristic linear response of Mariner at $\Delta R = \pm 10°$

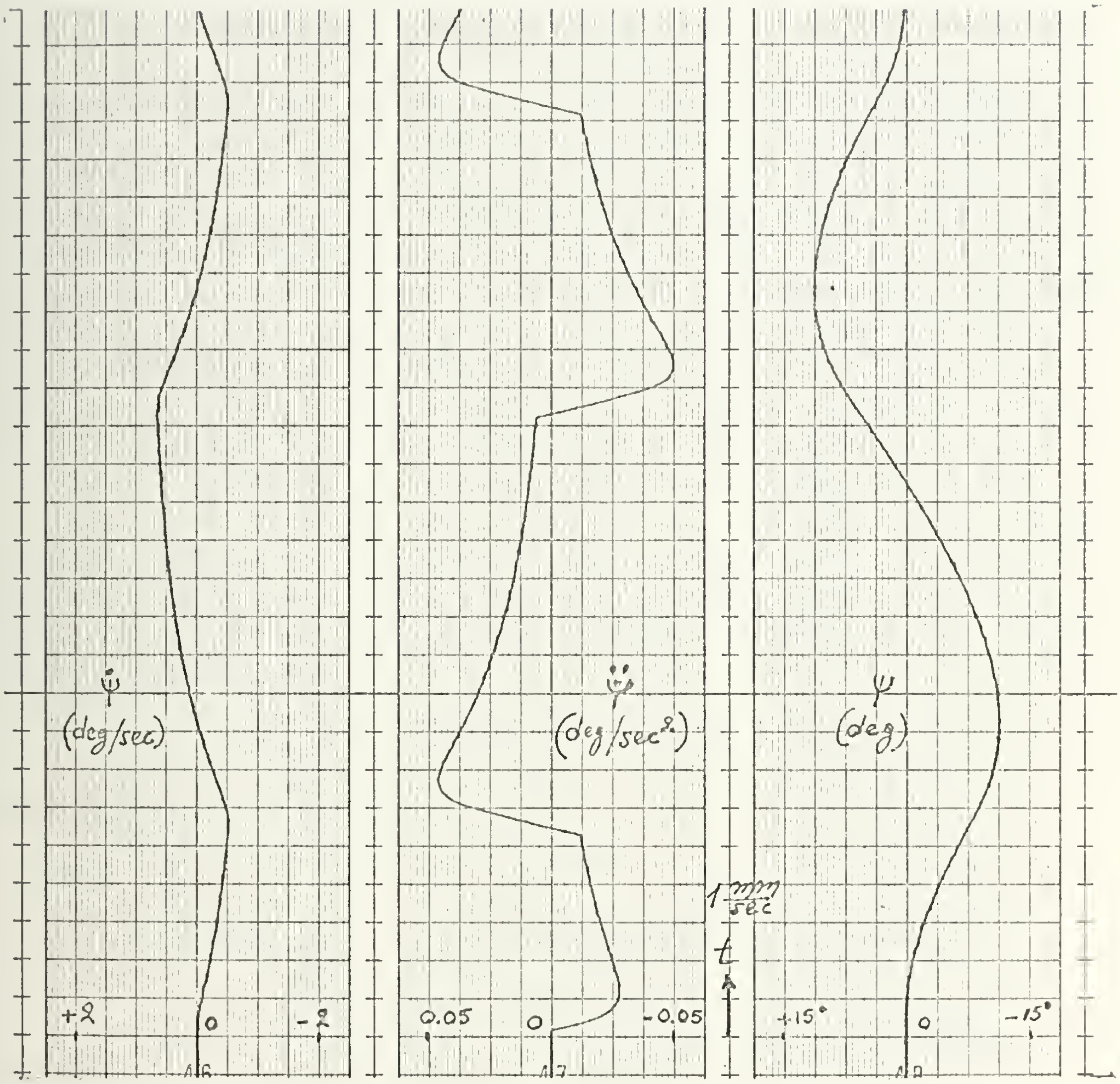


Figure 20-2. Characteristic linear response of Mariner at $\Delta R = \pm 10°$

which is balanced eventually with the outwards centrifugal force of the Mariner. The acceleration $\dot{v}$ is zero when this balance is accomplished.

The third phase of the turn is not developed because the rudder is given a negative −10° angle and the Mariner starts to turn starboard. It should also be noted here that at the instant the rudder is at −10° the center of the gravity of Mariner is at maximum port (negative) position. The process of turning +10° and −10° angle to the rudder was performed several times.

Figure 21 shows the linear response of the Mariner due to ± 5° angle of the rudder. The difference with the response obtained with ± 10° rudder is basically the smaller amplitudes.

Figure 22 shows the linear response of the Mariner due to a positive change of R.P.M. of the propeller speed of approximately 9 R.P.M. with respect to the equilibrium R.P.M. (corresponding to 15 knots).

The reference axes (x_o, y_o) are moving at a velocity 15 knots initially straight ahead as is the Mariner and consequently the (x,y) axes. The response is recorded by curves of calculated changes in the parameters $\psi, \dot{\psi}, \ddot{\psi}, y_o, \dot{y}_o, x_o, \dot{x}_o$. Initially the origin of the (x,y) axes in the Mariner with respect to the (x_o, y_o) axes is 250 ft on the x_o axes and 48 ft on the y_o axes. Note here that the computer unit, i.e. 100 volts, equals 160 ft for y_o axes and 550 ft for x_o axes respectively.

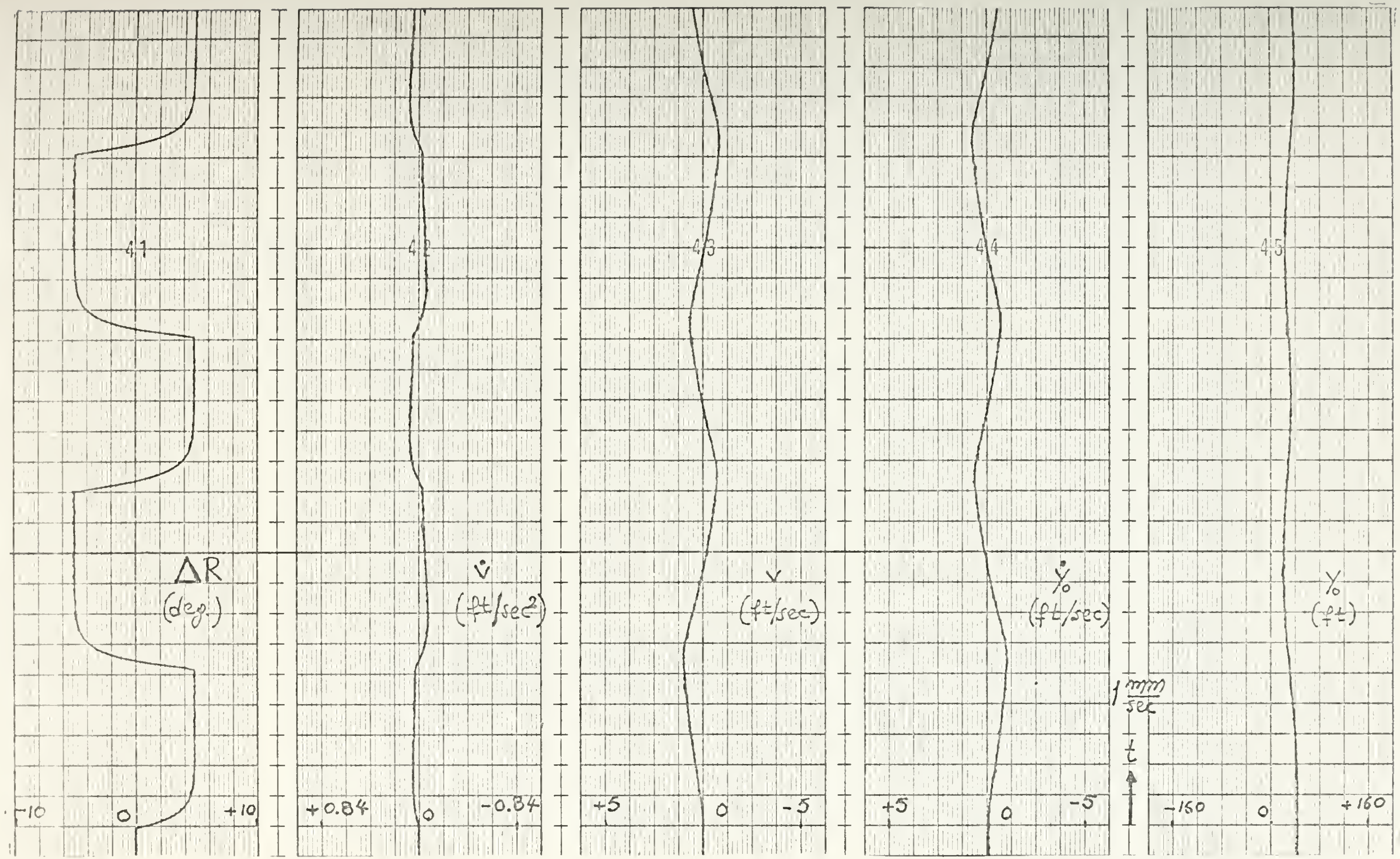


Figure 21–1. Characteristic linear response of Mariner at $\Delta R = \pm 5°$

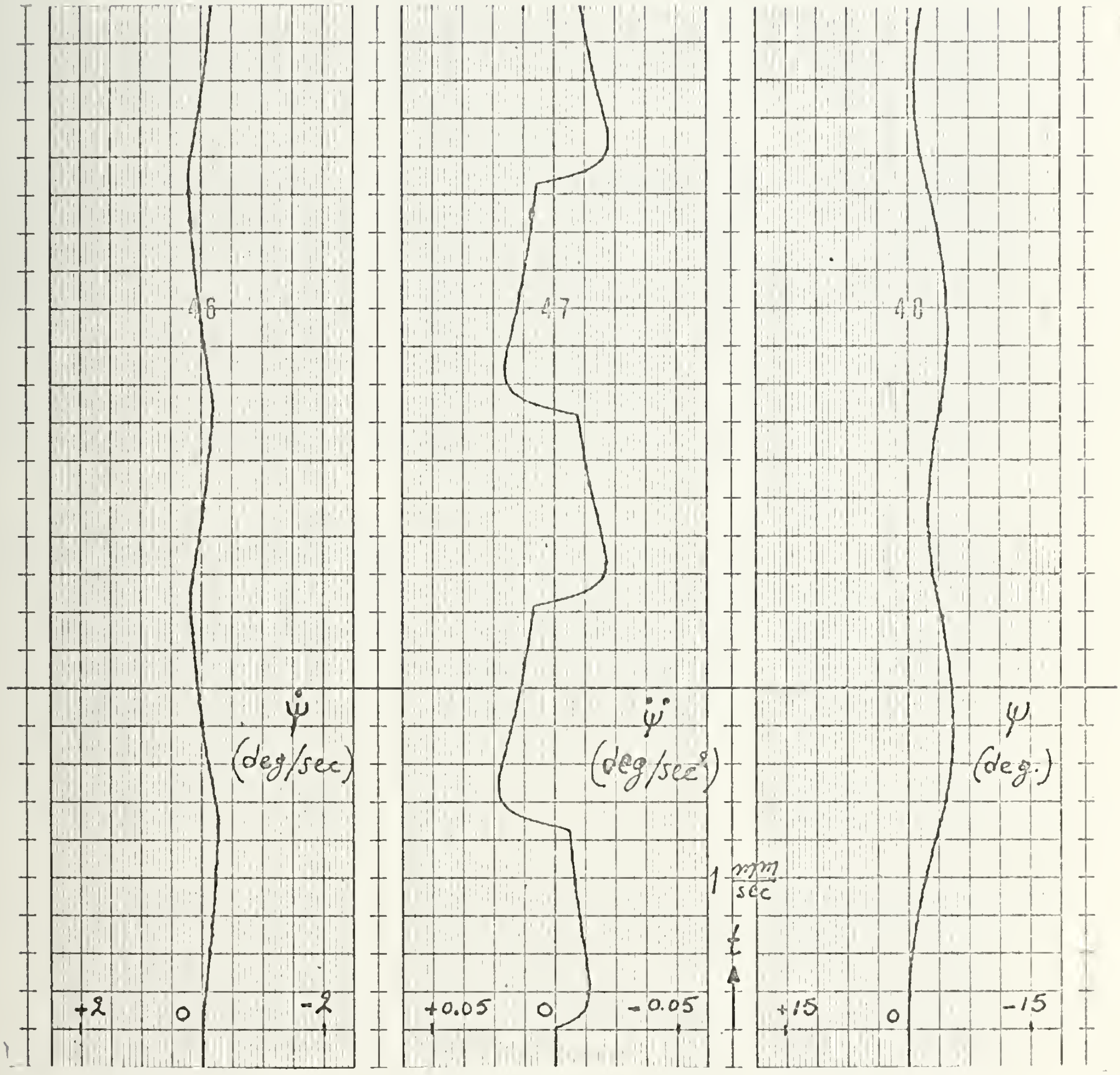


Figure 21-2. Characteristic linear response of Mariner at $\Delta R = \pm 5°$

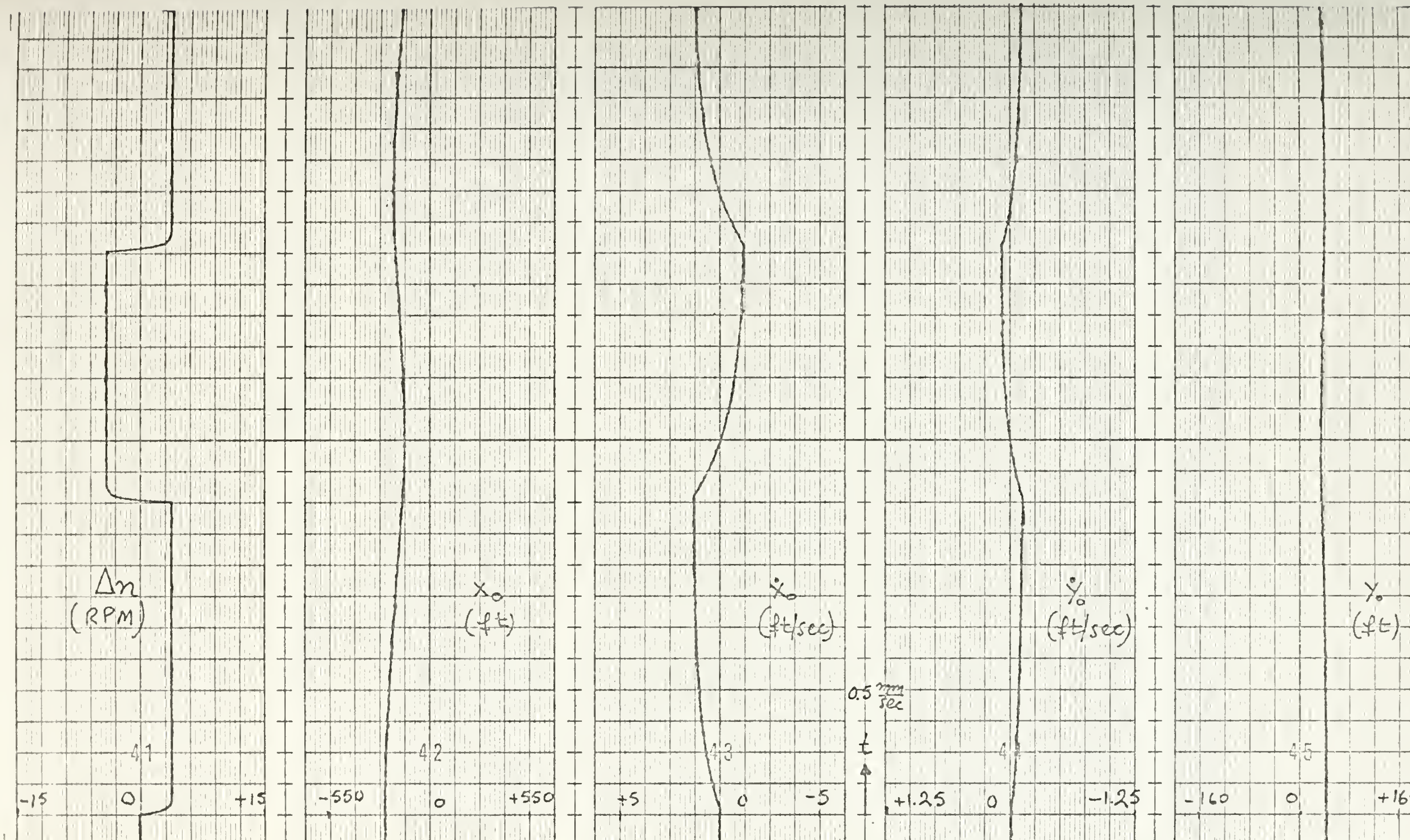


Figure 22–1. Characteristic linear response of Mariner at $\Delta n = \pm 9$ RPM

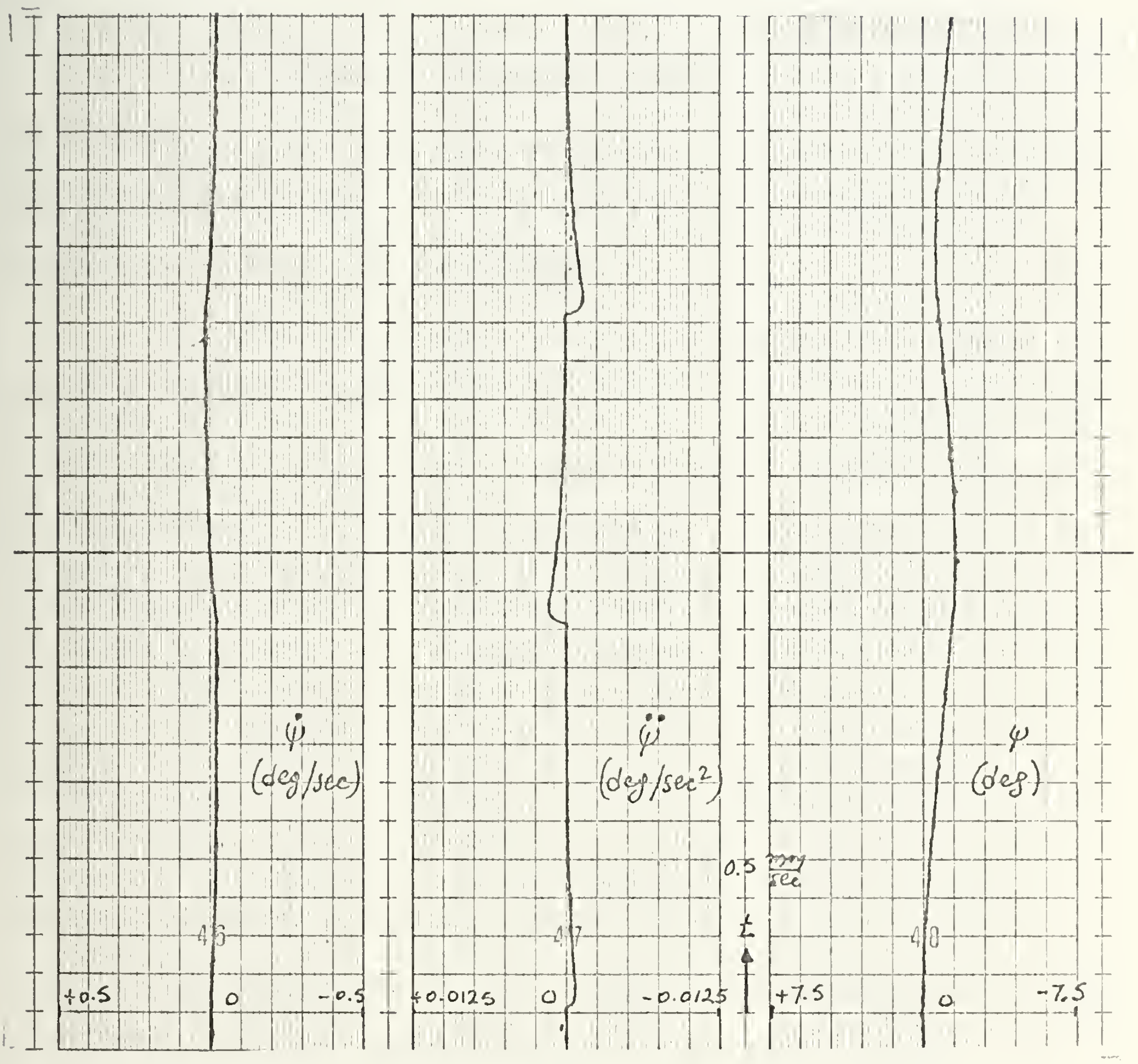


Figure 22–2. Characteristic linear response of Mariner at $\Delta n = \pm 9$ RPM

The movement in the direction x_o is due to the $X_n \Delta n$ term in equation (V-1). The origin of the (x,y) axes in the Mariner moves to the origin of the (x_o,y_o) axes in 110 sec approximately. The ship also yaws −1.5° approximately.

It should be noted here that only the force and moment due to the RPM propeller change are simulated. The force and moment due to the propeller equilibrium speed of 15 knots is neglected.

Figure 23 shows the characteristic linear response of Mariner obtained in terms of the calculated parameters $\Delta n, x_o, \dot{x}_o, \dot{y}_o, y_o, \dot{\psi}, \ddot{\psi}, \psi$ and caused $\pm$ 5 RPM change of propeller speed. Again the Mariner is assumed moving at 15 knots at equilibrium position. The initial position of the origin of the (x,y) axes was the same.

Figure 24 shows the linear response of the Mariner to a rudder change of approximately +0.562° (for P437=+0.0281) and a simultaneous +9RPM propeller speed change in terms of the calculated parameter perturbations x_o, $\dot{x}_o$, $\dot{y}_o$, y_o, $\dot{\psi}$, ψ, Δn, ΔR. Again initially the Mariner is moving straight ahead at 15 knots with rudder at midships. Then both the rudder and propeller speed change at +0.562° and +9 RPM respectively. This results in yawing moments which cancel each other (ψ=0). The only obtained perturbation is a change of location of the origin of the (x,y) axes on the Mariner but only along the x_o axes. Thus it is concluded that a rudder angle of about +0.562°

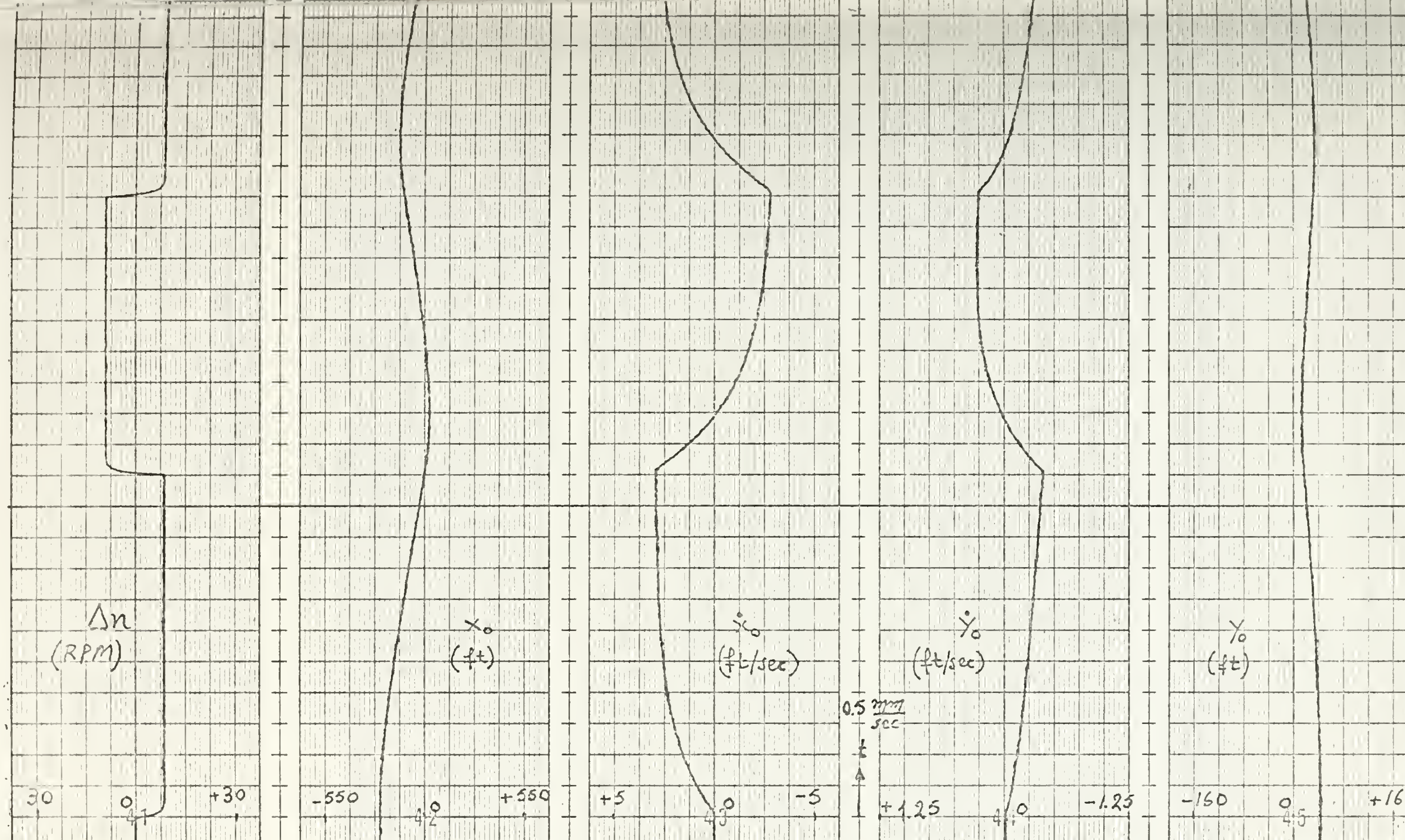


Figure 23—1. Characteristic linear response of Mariner at Δn = ± 5 RPM

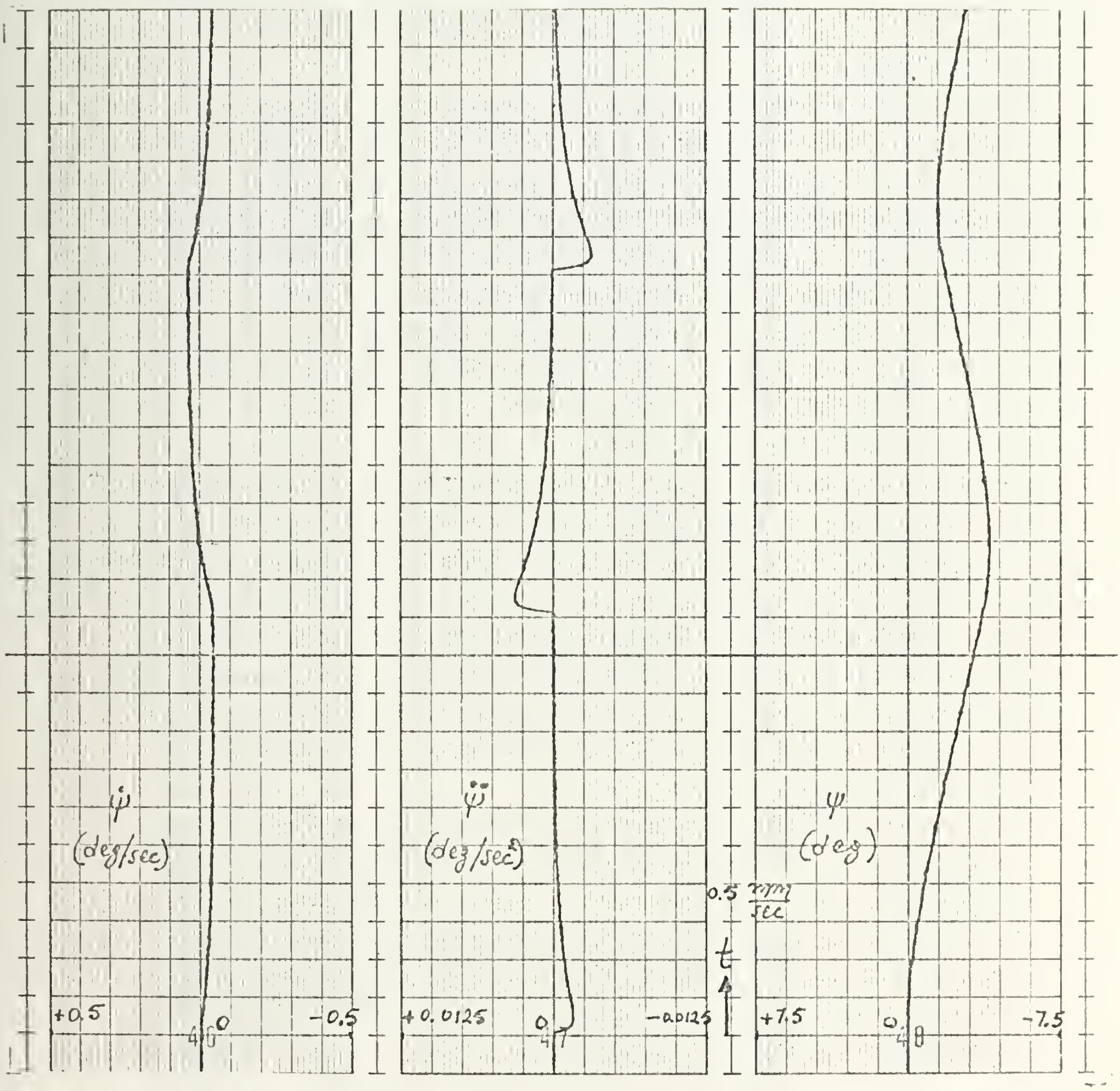


Figure 23-2. Characteristic linear response of Mariner at $\Delta n = \pm 5$ RPM

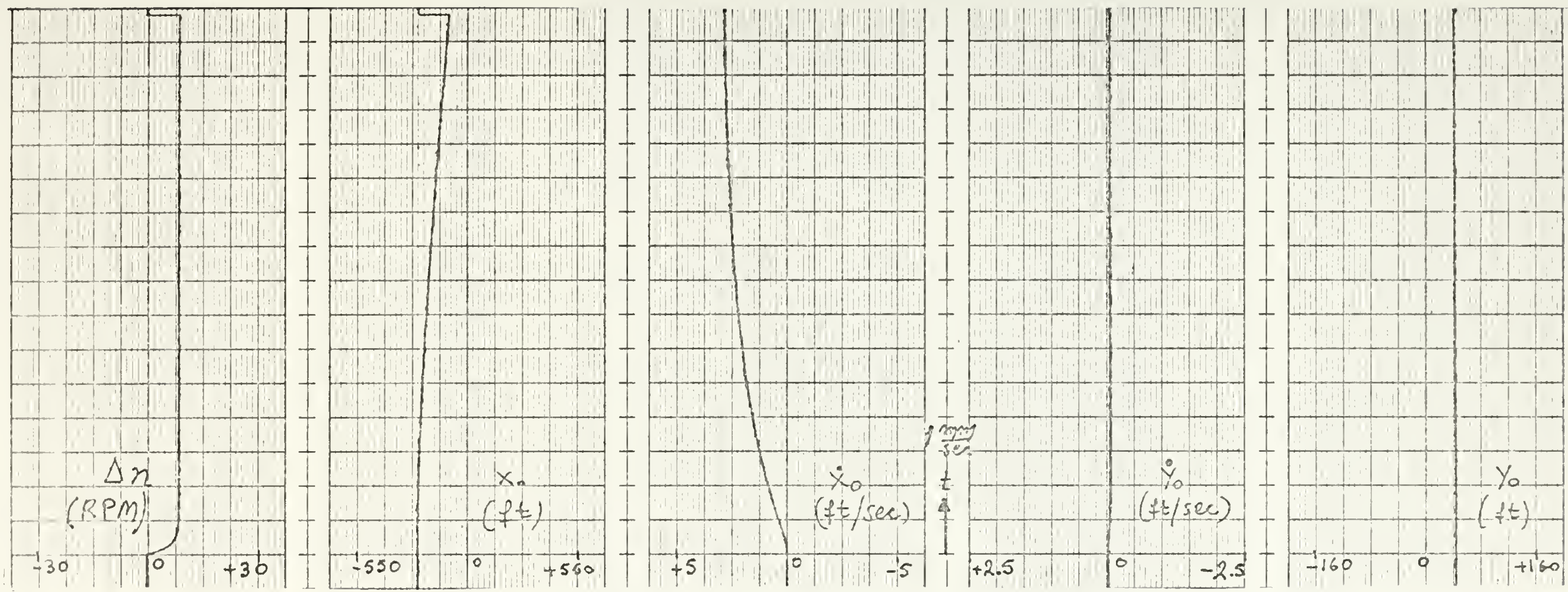


Figure 24–1. Characteristic linear response of Mariner at $\Delta R = +0.562°$
$\Delta n = +9$ RPM

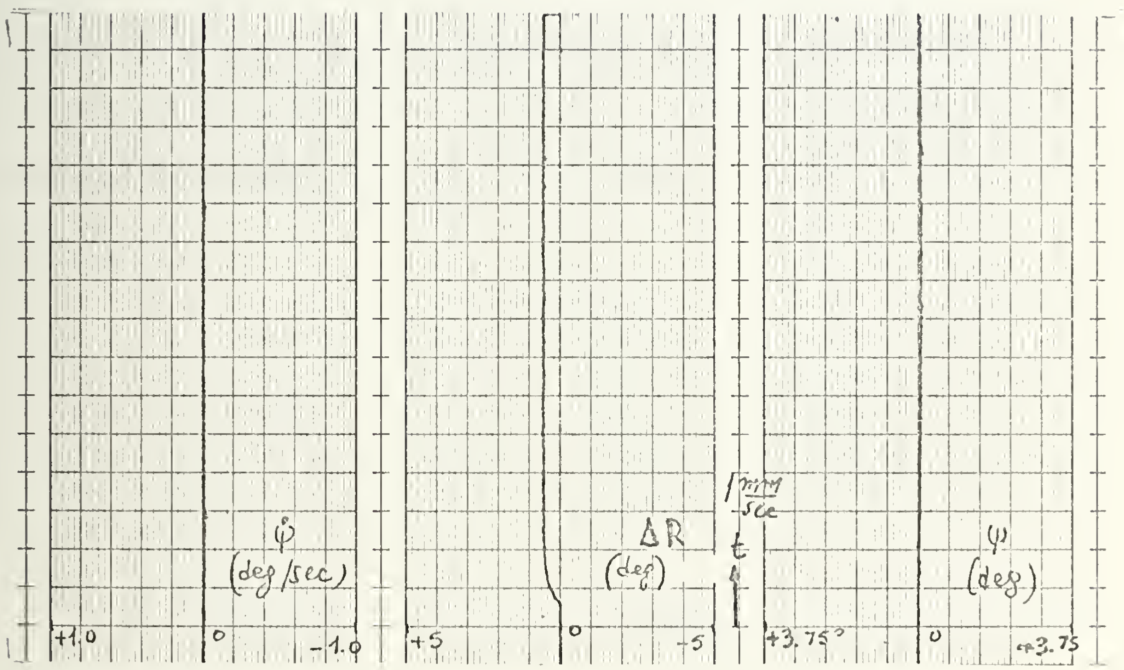


Figure 24–2. Characteristic linear response of Mariner at ΔR = + 0.562°, Δn = + 9 RPM

is enough to create a yawing moment necessary to cancel the yawing moment created by a change of +9 RPM of propeller speed. Figure 25 shows the response of the Mariner obtained in terms of the calculated perturbations of the parameters Δn, x_o, $\dot{x}_o$, $\dot{y}_o$, y_o, $\dot{\psi}$, ψ, ΔR and created by a simultaneous change in rudder angle and propeller speed at $\pm$ 5° and $\pm$ 9 RPM respectively. These curves can be analyzed analogously with the preceding curves. It is mentioned here that the same response was obtained for both ship No 1 and ship No 2 in all the previous cases.

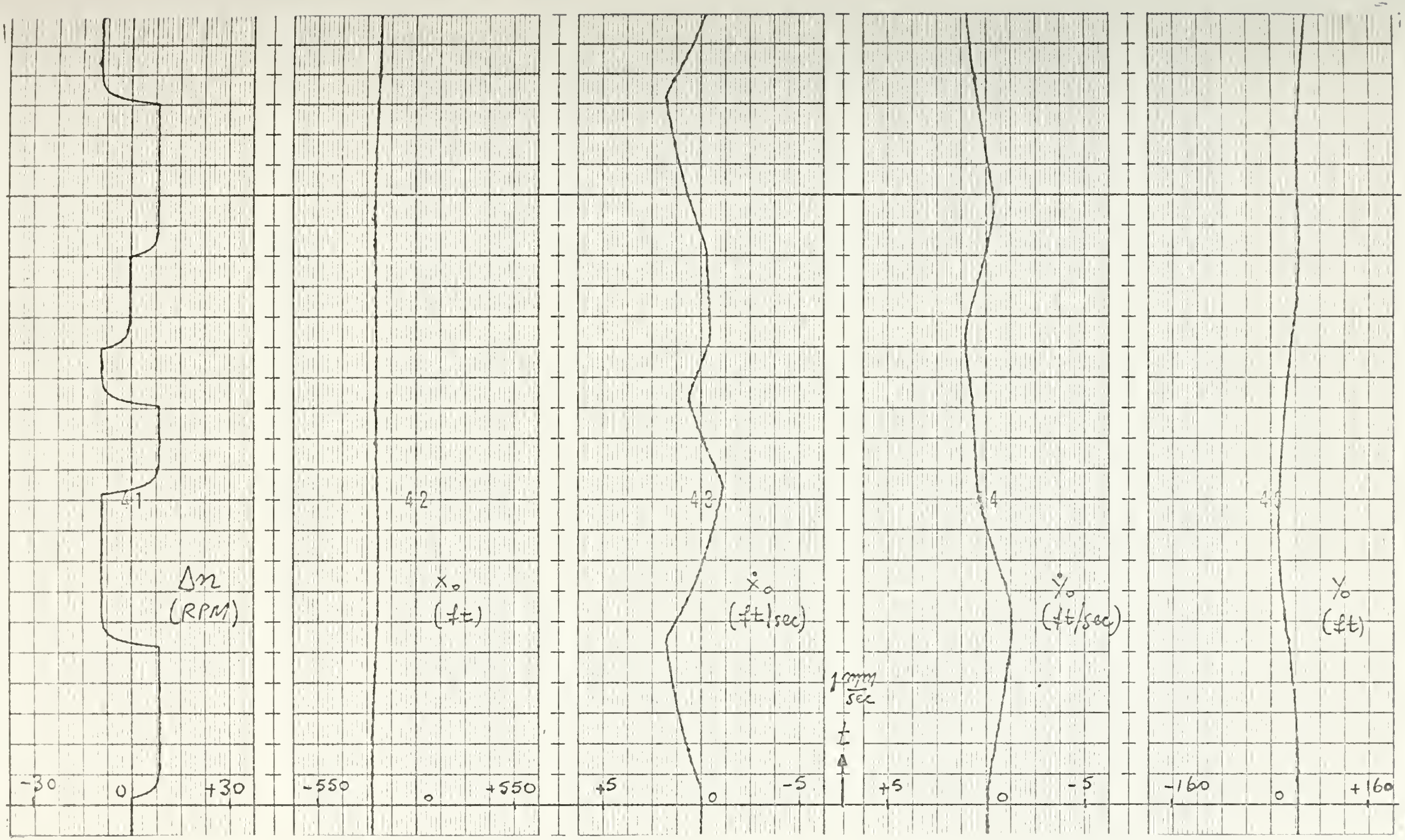


Figure 25-1. Characteristic linear response of Mariner at $\Delta R = \pm 5°$, $\Delta n = \pm 9$ RPM

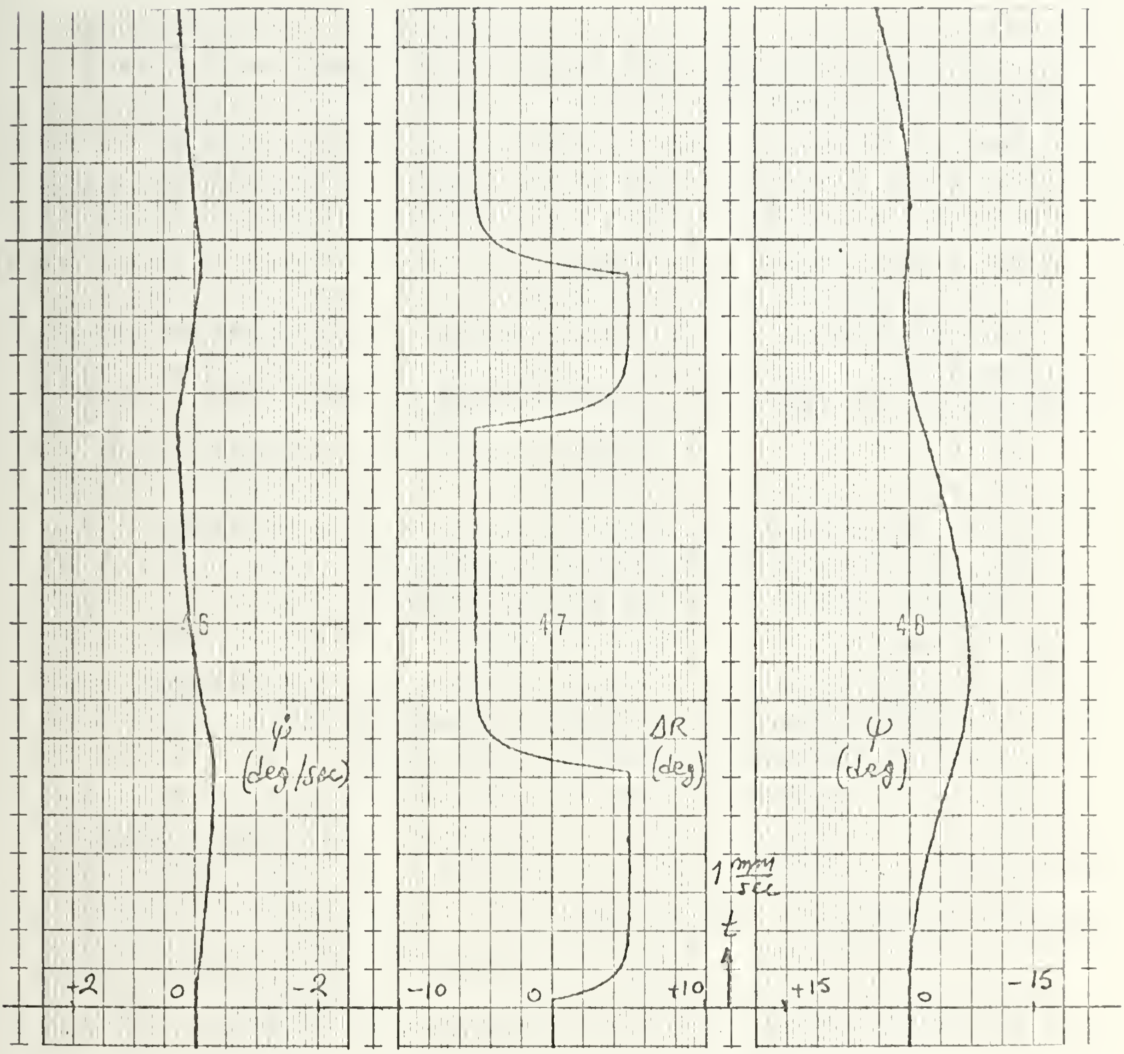


Figure 25–2. Characteristic linear response of Mariner at $\Delta R = \pm 5°$, $\Delta n = \pm 9$ RPM

VI. INTERACTION FORCES AND MOMENTS ARE INCLUDED

A. INTRODUCTORY DISCUSSION

During the UNREP operation the tracking (receiving) ship is usually keeping course to avoid collision and maintaining station relative to the leading (replenishing) ship. The leading ship must keep a steady course and keep oscillations about this course to a minimum. For this reason the remainder of this study is subdivided into the following sections, namely:

1. Phase I: Interaction forces and moments are included but are applied only to the leading ship as it is overtaken by the tracking ship.

2. Phase II: This phase considers the complete hybrid simulation of the UNREP operation including all the interaction forces and moments.

It is noted that in phase I the response of the leading ship is of interest. Further work in extending phase I will be the response of the tracking ship as it overtakes the leading ship so interaction forces and moments are applied to the tracking ship. This will be better understood after reading of next section, since it is related with how the interaction data curves are given. Briefly it can be mentioned that these data correspond to that case in which the interaction force and moment act on ship A as ship B overtakes it. So as a first case ship A is chosen to be the leading ship.

B. INTERACTION DATA CURVES—INTERPOLATION PROGRAMMING

Figures 26 and 27 show the nondimensional N moment and Y force respectively versus the longitudinal separation (α) between midships and the lateral separation (β). The generation of these curves by the analog computer exceeds its capability. Therefore these curves are made piecewise linear and stored on a digital computer namely the XDS-9300 machine. It should be mentioned here that in this stored array the points which correspond to 600 ft longitudinal distance (α) are included for both N-moment and Y-force. However these points are not shown on Figures 26 and 27 respectively. Computer program III shows the program necessary for a two-dimensional interpolation in two separate arrays for N-moment and Y-force respectively. It is mentioned that the longitudinal separation distance (α) can give negative or positive values but the lateral distance between ships (β) is restricted to positive values only. Figure 28 shows the geometry as far as longitudinal and lateral separation distances are concerned. It should also be mentioned that in phase I interaction moments and forces are applied only to ship A (see Figures 26, 27, 28) which corresponds to the leading ship because the data curves for the interaction effects are such. To apply interaction moments and forces to ship B, which corresponds to the tracking ship, the longitudinal separation distance should be sign inverted in order for it to give the

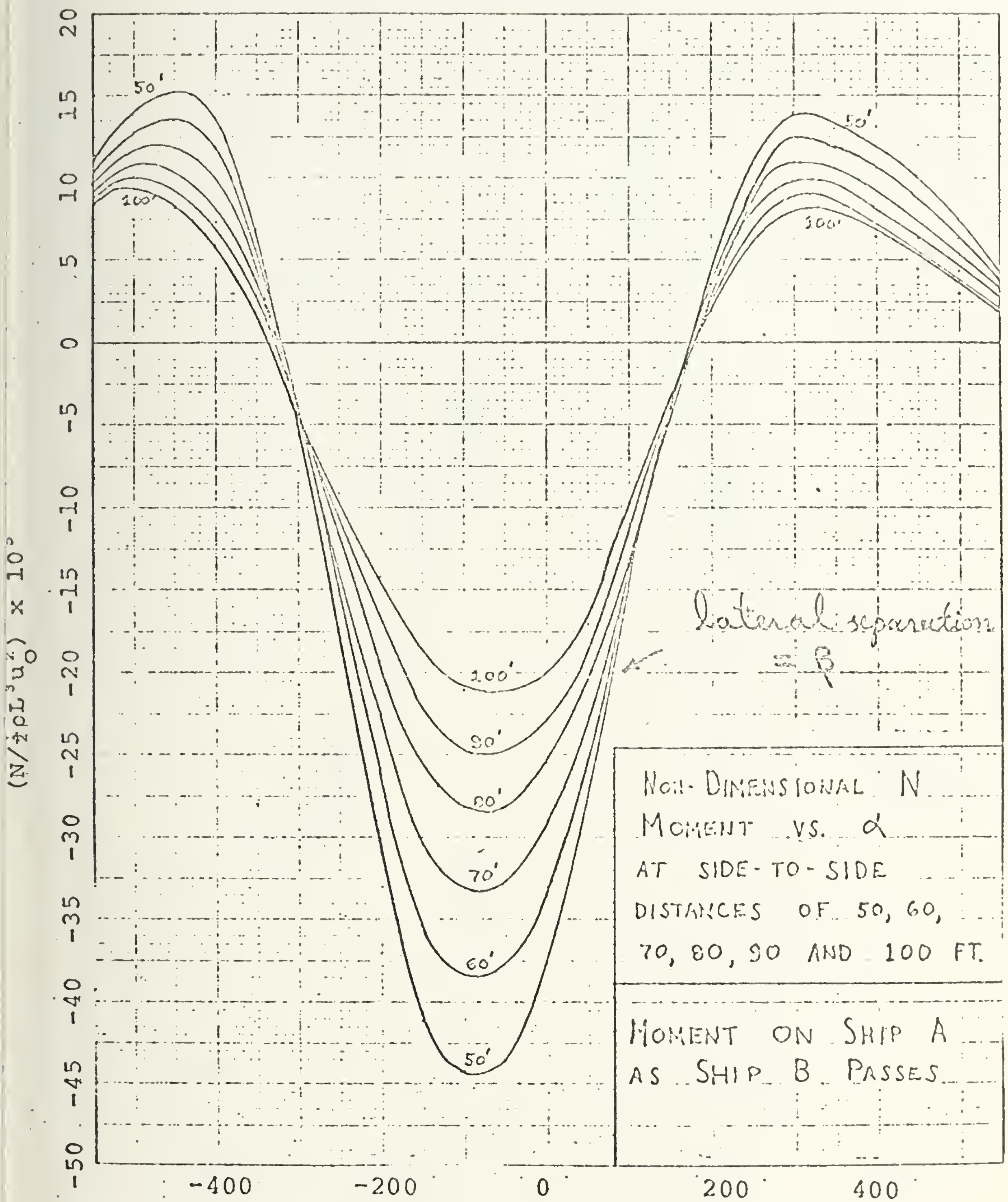


Figure 26. Dimensionless N Moment vs. Longitudinal Separation.

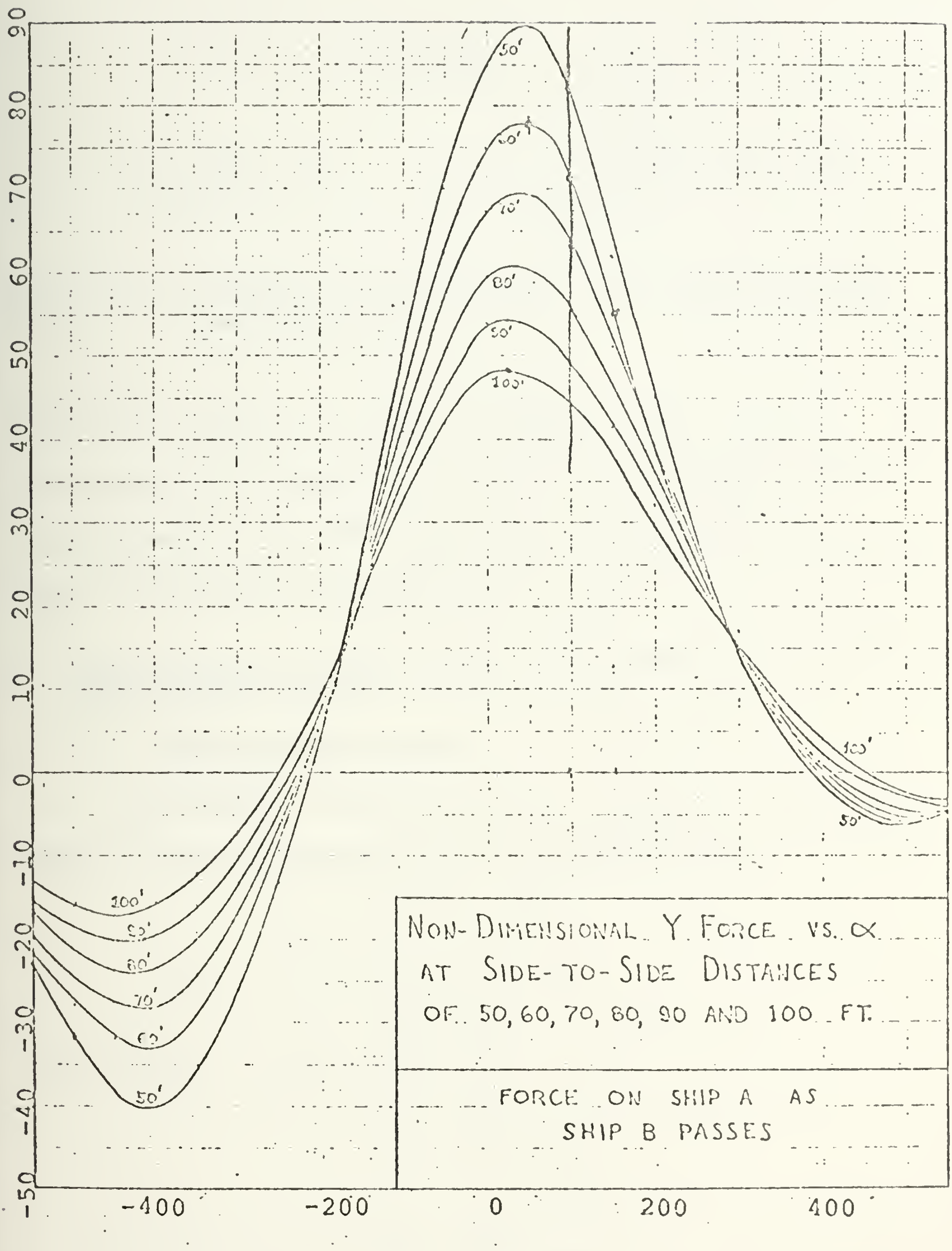


Figure 27. Dimensionless Y Force vs. Longitudinal Separation.

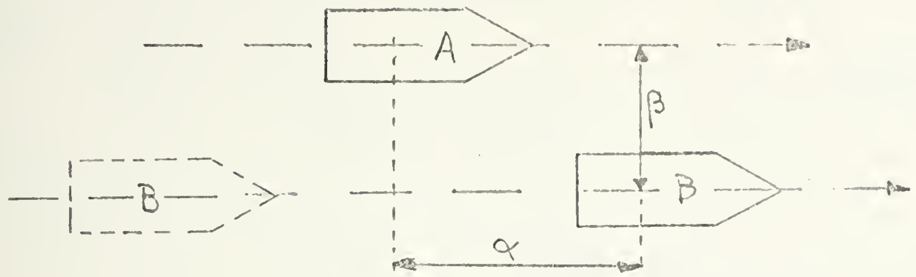


Figure 28. Geometry of longitudinal and lateral separation distances.

appropriate value for M and Y respectively. M and Y are vectors with opposite direction in the case of ship B as compared with those applied to ship A. Ships A and B are defined in Figures 26, 27, 28.

C. MEASUREMENT OF LONGITUDINAL AND LATERAL SEPARATION DISTANCE

1. Longitudinal Distance

To measure the longitudinal distance, α, between midships the following equation must be used:

$$\alpha = x_{o_1} - x_{o_2}$$

or

$$-\alpha = x_{o_2} - x_{o_1} \qquad \text{(VI-1)}$$

substituting in this equation:

$$\alpha = \bar{\alpha}\ \alpha_m$$

$$x_{o_2} = \bar{x}_{o_2}\ x_{o_{2m}}$$

$$x_{o_1} = \bar{x}_{o_1}\ x_{o_{1m}}$$

where $x_{o_{2m}}, x_{o_{1m}}, \alpha_m$ are the maximum expected values of these variables respectively, and $\bar{x}_{o_1}, \bar{x}_{o_2}, \bar{\alpha}$ are the

scaled variables whose values range from −1 to +1. Hence equations (VI−1) become:

$$-\bar{\alpha}\,\alpha_m = \bar{x}_{o_2} x_{o_{2m}} - \bar{x}_{o_1} x_{o_{1m}} \qquad \text{(VI−2)}$$

or

$$-\bar{\alpha} = \left[\frac{x_{o_{2m}}}{\alpha_m}\right] \bar{x}_{o_2} - \left[\frac{x_{o_{1m}}}{\alpha_m}\right] \bar{x}_{o_1} \qquad \text{(VI−3)}$$

Choosing: $\alpha_m = 550$ ft

$x_{o_{2m}} = 550$ ft

$x_{o_{1m}} = 550$ ft

equation (VI−2) becomes:

$$-\bar{\alpha} = \bar{x}_{o_2} - \bar{x}_{o_1} \qquad \text{(VI−4)}$$

Figure 29 shows the analog patching diagram necessary for equation (VI−4)

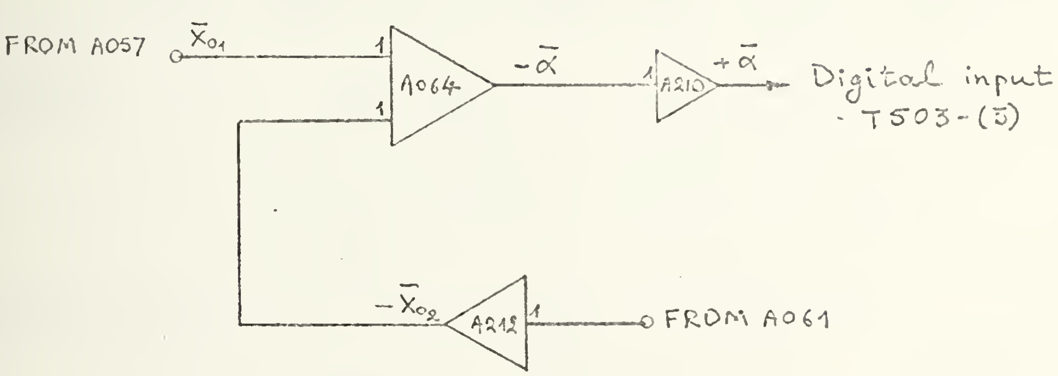


Figure 29. Longitudinal distance analog diagram.

2. <u>Lateral Distance</u>

To measure the lateral side−to−side distance between ships the following equation must be used:

$$\beta = y_{o_2} - y_{o_1}$$

or

$$-\beta = y_{o_1} - y_{o_2} \qquad \text{(VI-5)}$$

substituting in this equation:

$$\beta = \bar{\beta}\ \beta_m$$

$$y_{o_1} = \bar{y}_{o_1} y_{o_{1m}}$$

$$y_{o_2} = \bar{y}_{o_2} y_{o_{2m}}$$

where: $y_{o_{1m}}$, $y_{o_{2m}}$, β_m are the maximum expected values of these variables respectively, and $\bar{y}_{o_1}$, $\bar{y}_{o_2}$, $\bar{\beta}$ are the scaled variables whose values range from −1 to +1. Hence equation (VI-4) can be written as:

$$-\bar{\beta}\ \beta_m = y_{o_{1m}} \bar{y}_{o_1} - y_{o_{2n}} \bar{y}_{o_2} \qquad \text{(VI-6)}$$

or

$$-\bar{\beta} = [\frac{y_{o_{1m}}}{\beta_m}]\ \bar{y}_{o_1} - [\frac{y_{o_{2m}}}{\beta_m}]\ \bar{y}_{o_2} \qquad \text{(VI-7)}$$

Choosing:

$$\beta_m = 100 \text{ ft}$$

$$y_{o_{2m}} = 160 \text{ ft}$$

$$y_{o_{1m}} = 160 \text{ ft}$$

equation (VI-7) can be written as:

$$-\beta = [1.60]\bar{y}_{o_1} - [1.60]\bar{y}_{o_2} \qquad \text{(VI-8)}$$

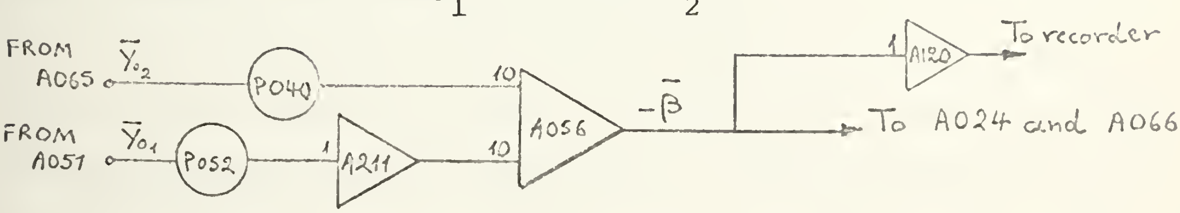


Figure 30. Lateral distance analog diagram.

Figure 30 shows the analog patching diagram needed for equation (VI-8).

It should be noted at this point that because the coefficients of $\bar{y}_{o_1}$ and $\bar{y}_{o_2}$ in equation (VI-8) are greater than 1, the pots are set as follows:

P040 = 0.1600 into a gain of 10

P052 = 0.1600 into a gain of 10

During the simulation $\bar{\beta}$ can take negative values but the data curves are given for positive values of $\bar{\beta}$ only. Thus in some way an absolute value should be provided either by digital subroutine ABS or by analog-patching configuration. The latter is chosen since the use of digital machine adds time delay in the simulation which may give rise to an error roughly of 5%.

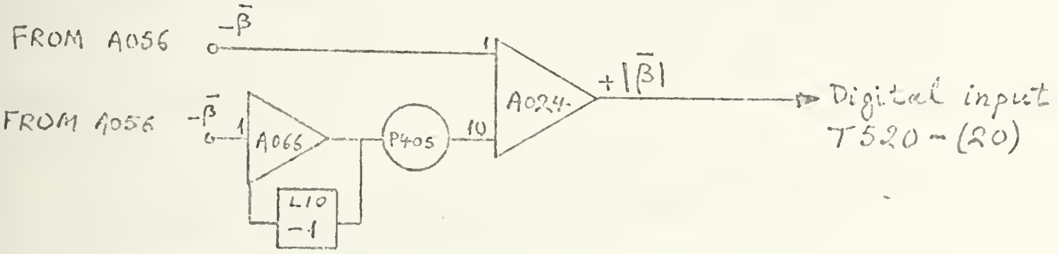
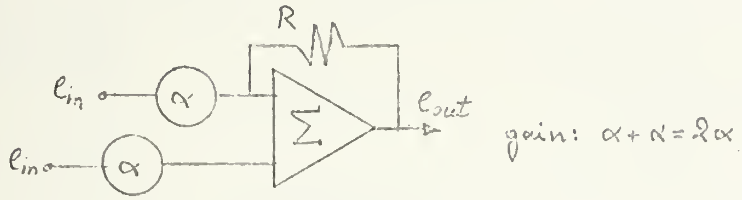


Figure 31a. Absolute value patching diagram of $|\bar{\beta}|$.

Figure 31a shows the analog patching diagram necessary to obtain the absolute value of $\bar{\beta}$.

It should be noted that in Figure 31a in the second input of A024 summer the gain is 10 but since: P405 = 0.2000 the gain becomes finally equal to 2. Also the limiter L 10 limits the output of A066 to negative values. More specifically $-|\beta|$ corresponds to +1 computer unit limit and

+ $|\overline{\beta}|$ corresponds to −1 computer unit limit respectively. However according to the following illustrated fact:



there is a better way of getting a gain of 2 since two resistors of value 1.0 M in parallel gives a value of 0.5 as value of input resistor which corresponds to a gain of 2 as shown next in Figure 31b.

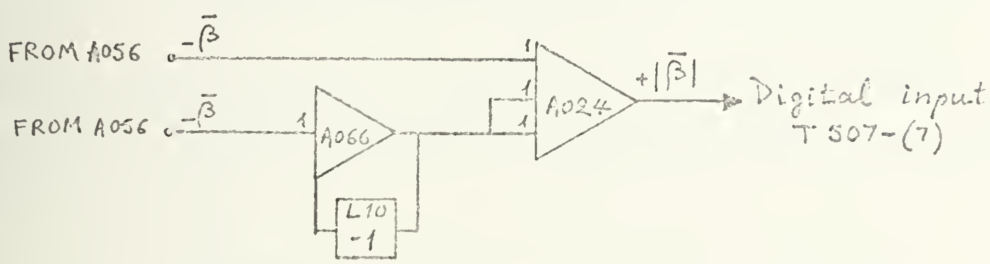


Figure 31b. Absolute value patching diagram of $\overline{\beta}$.

Finally the way of Figure 31b is chosen being more compact.

D. APPLICATION OF INTERACTION MOMENT N AND FORCE Y TO SHIP A (LEADING SHIP)

1. Introductory Discussion

Ship No 2 is chosen arbitrarily to be the ship A, that is the leading ship, on which moments and forces due to interaction effects would be applied. Figure 32 illustrates the way N moment and Y force are interpreted by hybrid operation of the machines.

The digital program which takes as data the values of $\overline{\beta}$, $\overline{\alpha}$, in the computer mode of hybrid operation, finds the

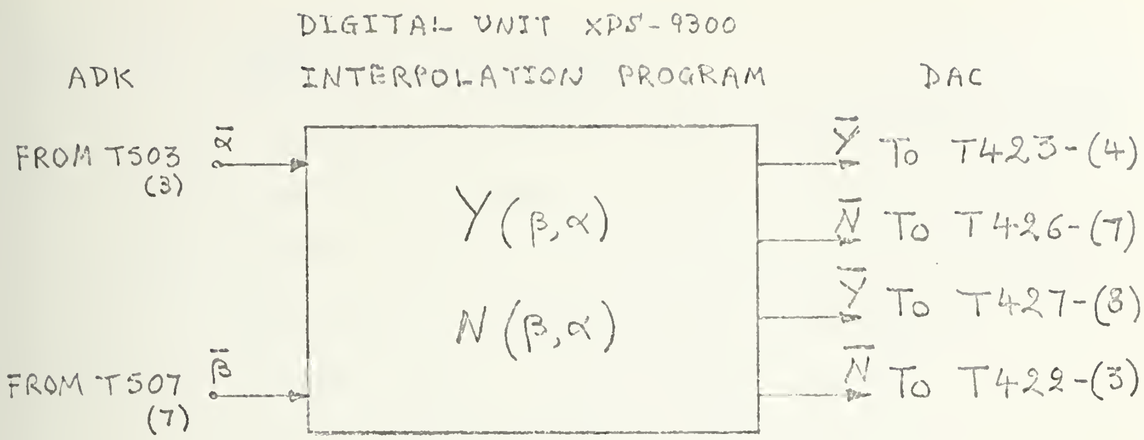


Figure 32a. Interpretation of N-moment and Y-force for hybrid computer operation.

corresponded values of N and Y and then gives back to the analog the values of N and Y, which are scaled quantities, takes care of:

a. Rescaling of $\bar{\beta}$, $\bar{\alpha}$ since $\bar{\beta} = 1.0$ and $\bar{\alpha} = 1.0$ corresponds to 100 ft and 550 ft respectively.

b. Making linear interpolation in the two-dimensional array. So it finds the corresponded nondimensional quantities of N' and Y'.

c. Since from the data curves, Figures 26, 27,

$N'_{max} = 44.5 \times 10^{-5}$

$Y'_{max} = 90.0 \times 10^{-5}$

hence, finding the dimensional values of N'_{max} and Y'_{max} namely

$$N_{max} = N'_{max} \times \tfrac{1}{2}\rho L^3 u_o^2 = 44.5 \times 10^{-5} \times 9.428 \times 10^{10}$$
$$= 4.195 \times 10^7 \text{ lbs-ft}$$

and $$Y_{max} = Y'_{max} \times \frac{1}{2}\rho L^2 u_o^2$$

$$= 90.0 \times 10^{-5} \times 17.87 \times 10^7 = 1.608 \times 10^5 \text{lbs}$$

$$= 72.9 \text{ tons}$$

d. Finding from N' and Y' the dimensional values of N' and Y' respectively as follows:

$$N = N' \times \frac{1}{2}\rho L^3 u_o^2 = N' \times 9.428 \times 10^{10}$$

$$Y = Y' \times \frac{1}{2}\rho L^2 u_o^2 = Y' \times 17.87 \times 10^7$$

e. Scaling both N and Y quantities taking in consideration the fact that the subroutine DAC multiplies each number given to the analog terminal by a factor of 100 i.e. it converts in computer units, so:

$$NSCALE = N/N_{max}$$

$$YSCALE = Y/Y_{max}$$

Computer program VA contains the source deck as well as the potentiometer values and amplifier addresses used for phase I.

Computer program VB contains the source deck used for phase I, but ship A (leading ship) was in that case the second model of the Mariner. The difference was only in the trunk lines which were used in the previouse case. In Figure 32 the trunk lines T426, T427 belong to the ship model No 1.

2. Dynamical Representation of Interaction Moment and Force—Analog Programming

Recalling Newton's laws of motion, equation (III-1) and since the study is done for the ship to be in 3 degrees

of freedom, equations (III–6), (V–1), (V–4), the application of the external interaction N–moment and Y–force are going to be an additional term in the yaw and sway equation respectively. Considering the dimensional form of the linearized equations of motion, equations (V–4) will become for ship No 2

$$\dot{\bar{u}} = [\frac{X_u u_m}{D_{21}}]\ \bar{u} + [\frac{X_n \delta n_m}{D_{21}}]\ \overline{\delta n}\ ,\ \text{Surge}$$

$$\dot{\bar{U}} = [\frac{Y_v v_m}{D_{21}}]\ \bar{v}\ [\frac{(Y_{\dot\psi} - mu_o)\dot\psi_m}{D_{22}}]\ \dot{\bar{\psi}} + [\frac{Y_{\ddot\psi}\ddot\psi_m}{D_{22}}]\ \ddot{\bar{\psi}}$$

$$+ [\frac{Y_{\delta R}\delta R_m}{D_{22}}]\ \overline{\delta R} + [\frac{Y_{\delta n}\delta n_m}{D_{22}}]\ \overline{\delta n} + \underbrace{\frac{Y}{D_{22}}}_{\text{additional term}}\ ,\ \text{Sway}$$

$$\ddot{\bar{\psi}} = [\frac{N_v v_m}{D_{23}}]\ \bar{v} + [\frac{N_{\dot\psi}\dot\psi_m}{D_{23}}]\ \dot{\bar{\psi}} + [\frac{N_{\dot v}\dot v_m}{D_{23}}]\ \dot{\bar{v}}$$

$$+ [\frac{N_{\delta R}\delta R_m}{D_{23}}]\ \overline{\delta R} + [\frac{N_n \delta n_m}{D_{23}}]\ \overline{\delta n} + \underbrace{\frac{N}{D_{23}}}_{\text{additional term}}\ ,\ \text{Yaw}$$

(VI–9)

where: $D_{21} = (m - X_{\dot u})\dot u_m = 1.07 \times 10^6$ lbs

$D_{22} = (m - Y_{\dot v})\dot v_m = 1.864 \times 10^6$ lbs

$D_{23} = (I_z - N_{\ddot\psi})\ddot\psi_m = 2.777 \times 10^7$ lbs–ft

Y = interaction force

N = interaction moment

It is clear from equation (VI–9) that the surge equation remains unchanged to interaction effects and

only sway and yaw equations have each of them one additional term respectively. Thus for the analog programming of equation (VI–9) it is only necessary to add the circuitry shown in Figure 33a to the patching diagram of Figure 19b. Note in this Figure:

$$P042 = \frac{N_{max}}{D_{23} x10} = \frac{4.195x10^7}{2.777x10^8} = 0.1511$$

Here there is a factor of division by 10 since the value $(N_{max}/D_{23}) > 1$ and so it is necessary to feed amplifier A036 in a gain of 10. Note that since in amplifier A036 we need one more, not available, input gain of 10, a separate internal resistor of 0.1 MΩ is used through the summing junction (SJ) of A036 giving the required gain of 10. Also:

$$P017 = \frac{Y_{max}}{D_{22}} = \frac{1.608x10^5}{1.017x10^6} = 0.1581$$

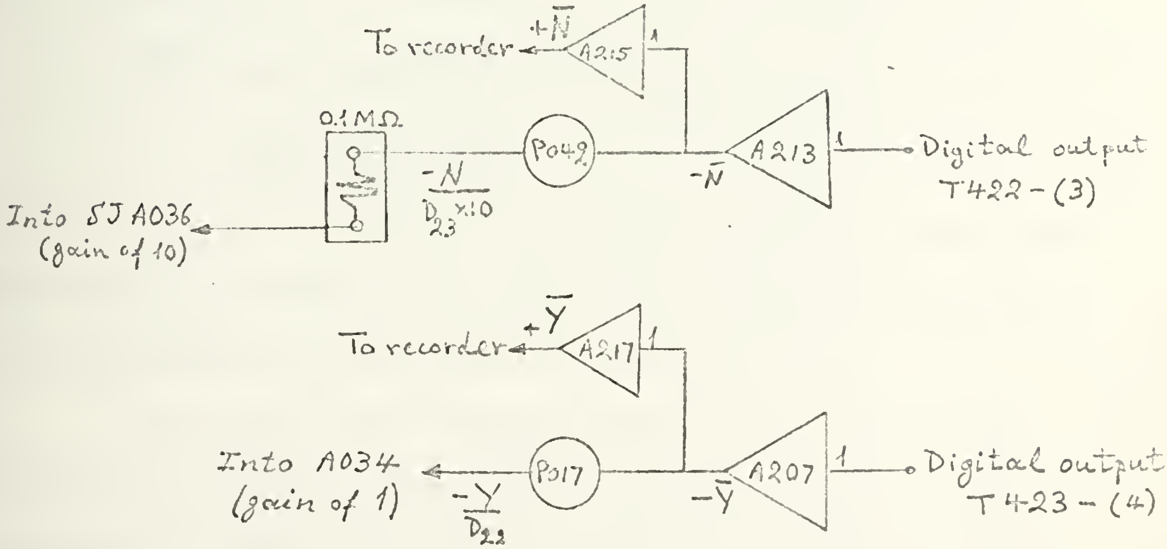


Figure 33a. Analog Diagram programming of interaction N–moment and Y–force for ship A (No 2).

For the ship model No 1 the analog patching circuitry of Figure 33b was added to this of Figure 19a whenever it was desired to be used as leading ship and ship model No 1 to be used as tracking ship respectively.

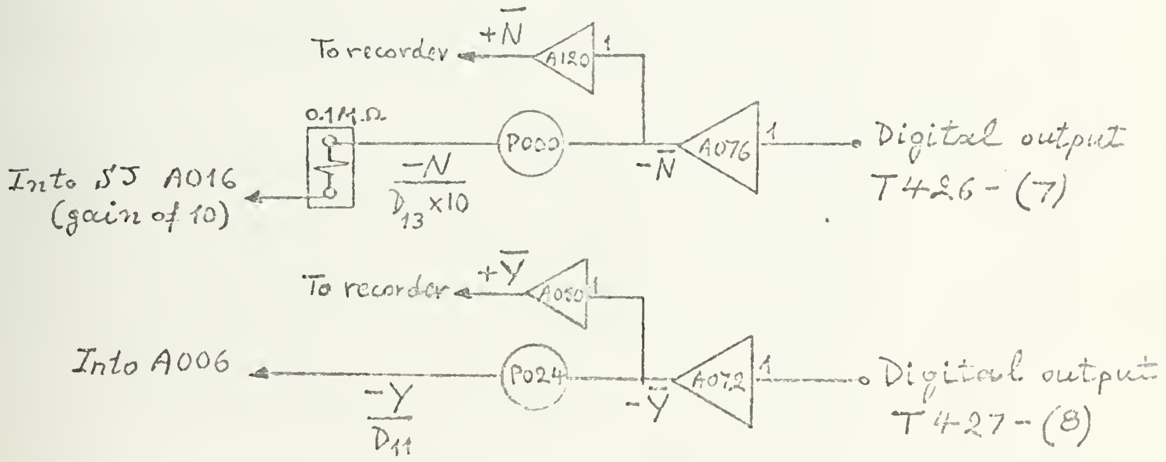


Figure 33b. Analog diagram programming of interaction N-moment and Y-force for ship model No 1.

It must be mentioned here that for Phase II where interaction effects have to be applied on both ships, both the configurations of Figures 33a and 33b must be used.

3. <u>Obtained Responses for Phase I</u>

a. Stationary runs (i.e. both ships have same propeller speed)

Figure 34a,b shows the obtained linear response of the leading ship (ship A) in terms of the calculated parameters Y, N, $\dot{y}_o$, α, β, v, $\dot{v}$, ψ .

Originally the leading ship was placed at the origin of the space coordinate system (x_o,y_o) and the tracking ship was placed at x_o = +524 ft and y_o = +70 ft.

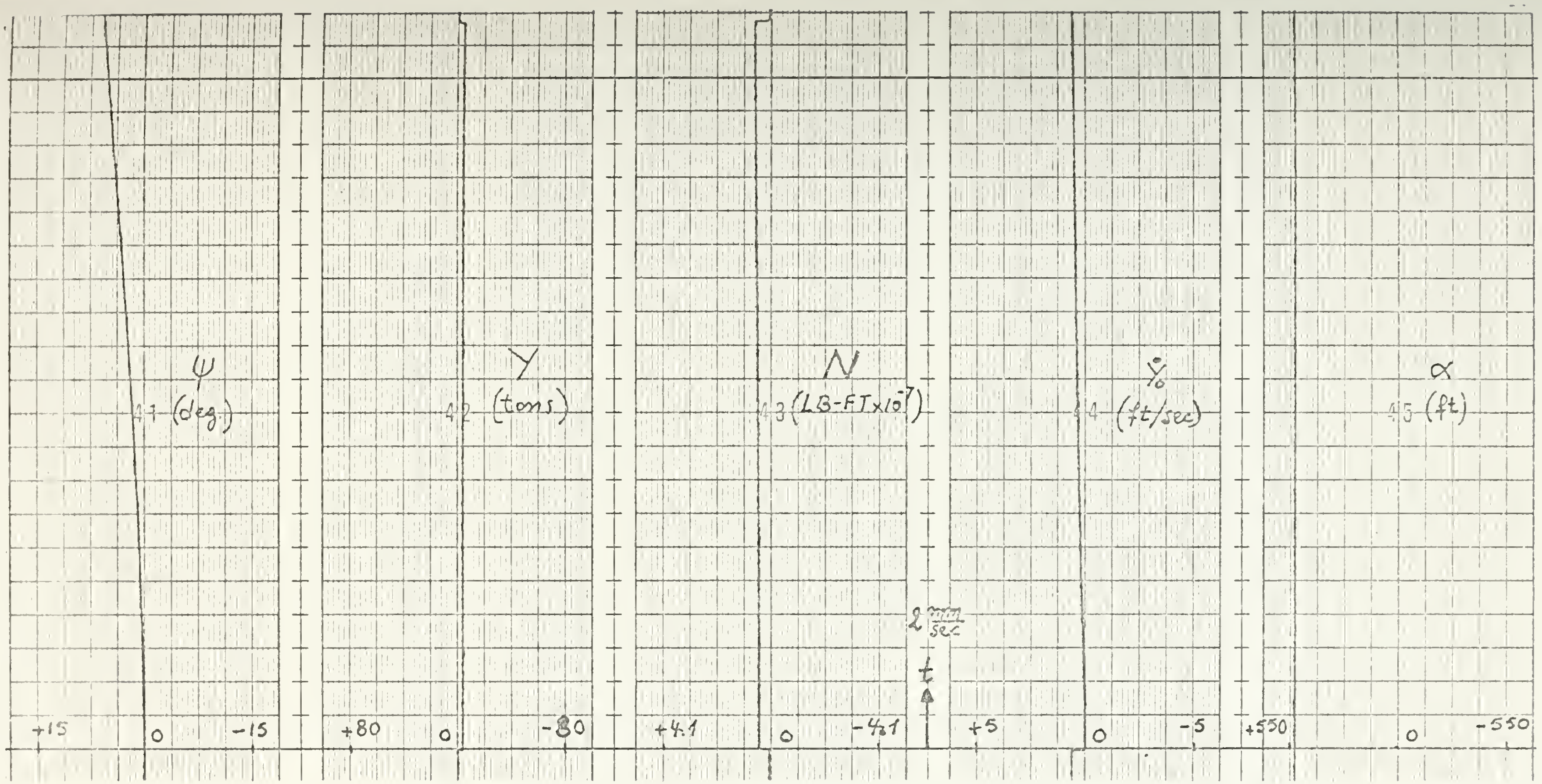


Figure 34a. Linear response of leading ship for Phase I. ($\Delta R=0, \delta n=0, \alpha=+524$ ft, $\beta=70$ft)

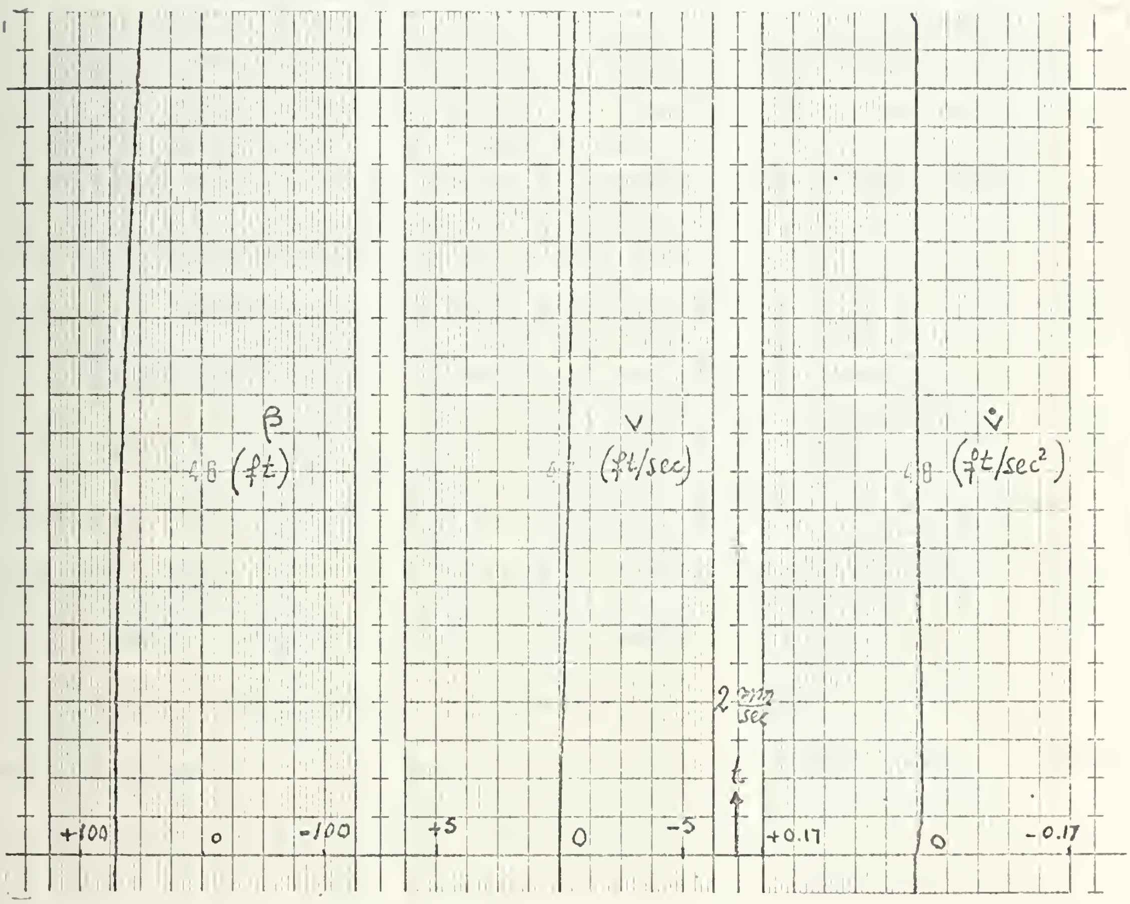


Figure 34b. Linear response of leading ship for Phase I. ($\Delta R=0$, $\delta n=0$, $\alpha=+524$ ft, $\beta=70$ ft)

Then both the ships were left to run with the same propeller speed which was 15 knots. The same speed of 15 knots was assumed for the origin of the space coordinate system (x_o, y_o).

The leading ship was forced to yaw to positive yaw angle due to the additional term of the interaction moment N. The interaction force Y produced a lateral acceleration and lateral velocity which forced the leading ship to move laterally decreasing continuously the lateral separation distance. In the sway equation (VI-9) not only the Y-force term was acting but the derivatives $Y_v, Y_{\dot{\psi}}, Y_{\ddot{\psi}}$ were producing additives effects since due to the yaw angle a change of yaw angle and rate of yaw angle change were obtained. It is also noted that the interaction force Y and moment N are slightly increased during the run since the lateral separation was decreasing. Similar results were obtained for the second run in which the leading ship was again placed originally at the origin of (x_o, y_o) axes and the tracking at $x_o = -524$ ft and $y_o = +70$ ft. Again the origin of the (x_o, y_o) was moving at 15 knots as well as both the leading and tracking ship. The response was calculated in terms of the perturbed parameters, $\psi, y, N, \alpha, \beta, v, \dot{v}$ as shown in Figure 35. The lateral distance during this second run was decreasing faster since the values for interaction force-Y and moment-N were greater. Obviously from the data curves both force Y and moment N are not symmetrical about the origin.

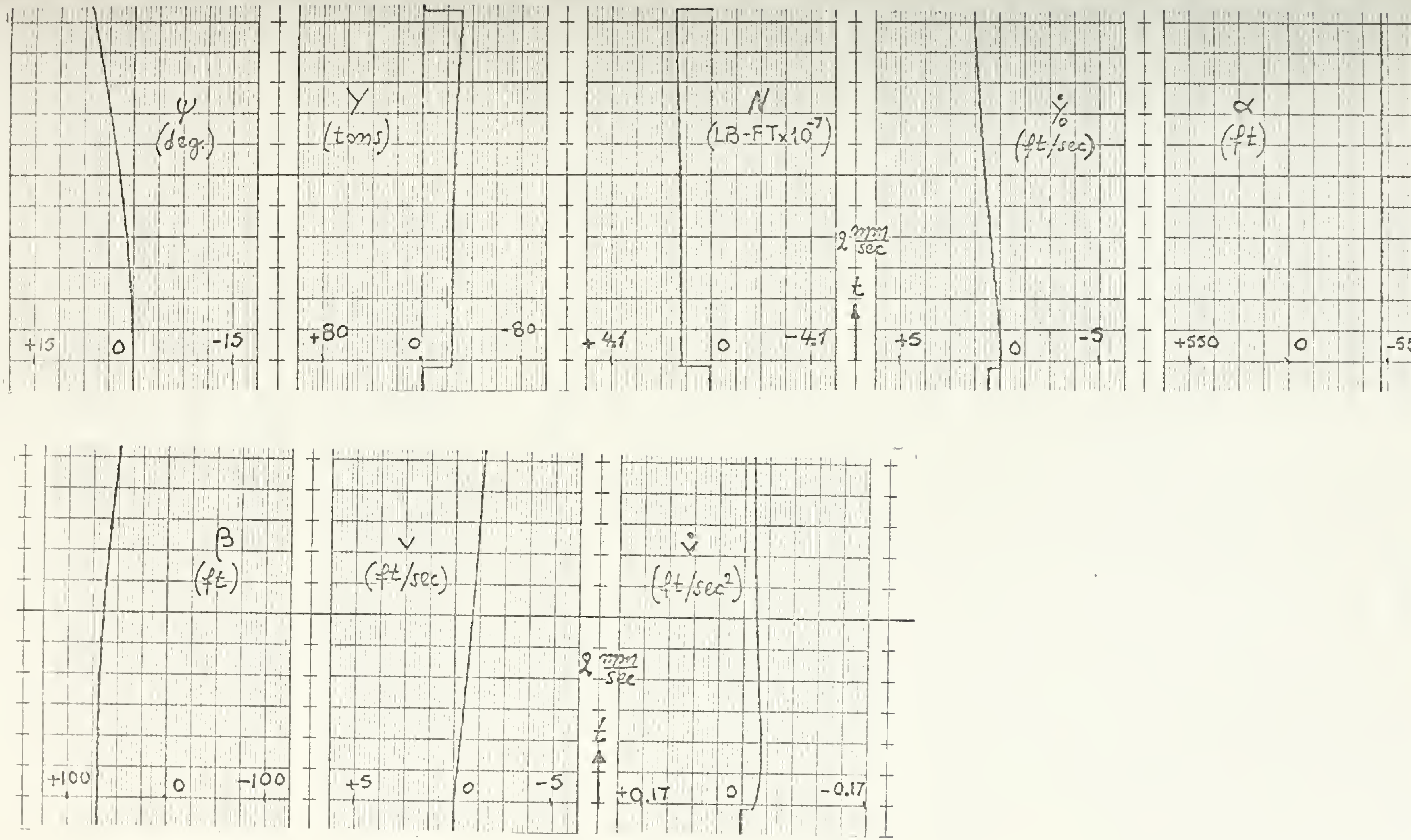


Figure 35. Linear response of leading ship for Phase I.
($\Delta R=0$, $\delta n=0$, $\alpha= -524$ft, $\beta= 70$ ft)

Figure 36 shows the response of the leading ship when the longitudinal distance and the lateral distance were set equal to zero and 70 feet respectively at the beginning of the run. Now because the longitudinal distance is zero, the Y-force and N-moment have not only greater values than previously but the leading ship yaws to negative yaw angles. This has as effect a negative lateral velocity and an acceleration initially which eventually reduces the interaction force-Y and moment-N drastically, but the lateral distance is increasing now since the velocity along the y_o-axis has opposite sign.

For all the above three responses the rudder for both the ships was set at zero, i.e. = 0. It should be noted at this point that the hybrid simulation program (computer program V) was made to work between lateral separation distances 100 ft and 50 ft since data are given for this range. The increase of the lateral distance is due:

a. To the negative yaw angle. From equation (V-2) it seems that eventually the term ($u \sin \psi$) becomes predominant over the term ($u \cos \psi$) hence even if a positive value is obtained for the v velocity a negative value of $\dot{y}_o$ is actually applied to the leading ship.

b. The negative yaw angle is obtained because for $\alpha=0$, $\beta=70$ ft a negative moment N is applied.

It has been mentioned previously that the two models are identical. So for Phase I No 2 model has chosen to be ship A, i.e. leading ship. To complete our work for

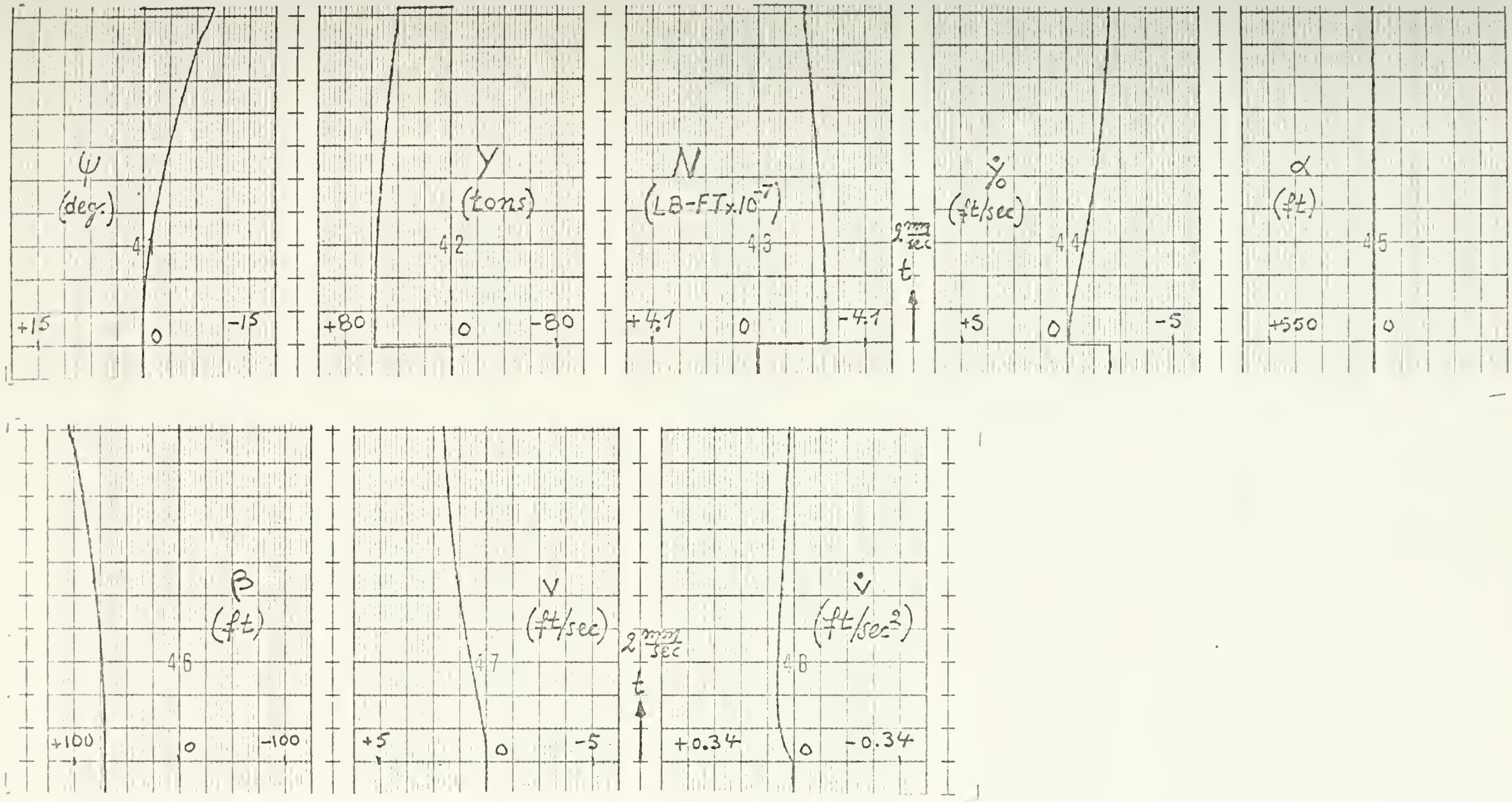


Figure 36. Linear response of the leading ship for Phase I.
($\Delta R=0$, $\delta n=0$, $\alpha=0$, $\beta=+70$ ft)

Phase I and check the wiring for model No 1 the case was reversed and ship A was the No 1 model and ship B the No 2 model. Remember ship B is always the tracking ship. For this last case a change in wiring on the analog board was made for the circuit representing the absolute value of the lateral separation distance (β). The change was due to the lack of operation of the limiter L 10 as was shown in Figure 31a and 31b.

The following configuration is used from now on for the absolute value of the lateral distance (β) as is next shown in Figure 37.

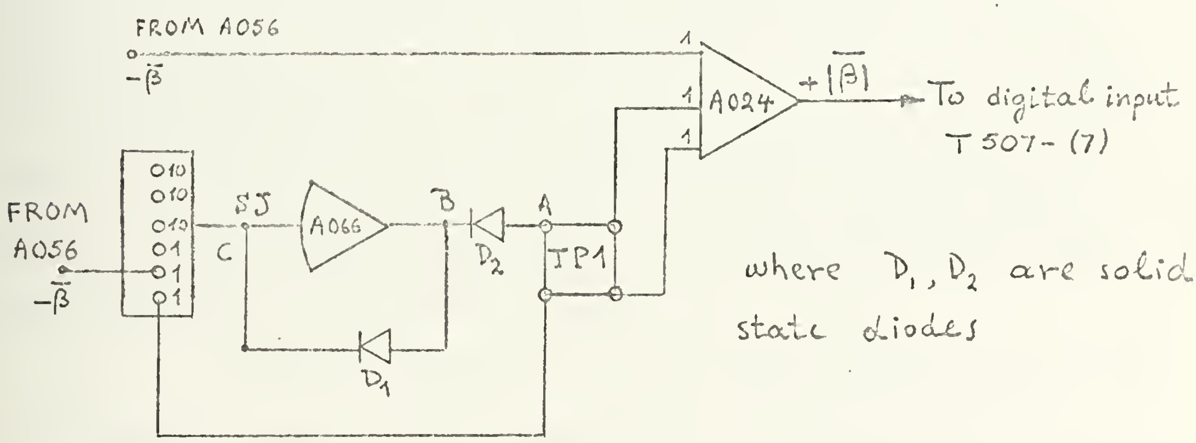


Figure 37. Absolute value patching diagram of the lateral distance.

Just briefly is mentioned that it is desired to keep the voltage of point A between the limits 0 and $-\infty$. This is because diodes D_1, D_2 are connected in such a way. Now when point C has a positive voltage D_1 is OFF and point B has a negative voltage hence point A has a positive voltage since D_2 is conducting. When point C is negative,

voltage D_1 is ON and B has about 0 or +0.5 volts voltage which is not enough to break down D_2 hence point A is at zero voltage.

Figures 38 and 39 show the obtained response for the leading ship, when the longitudinal distance is +400 feet and −400 feet and the lateral distance +70 feet from the tracking ship. The response was obtained in terms of the perturbated parameters ψ, y, N, $\dot{y}_o$, α, β, v, $\dot{v}$. The ships were moving at the same speed of 15 knots with the leading ship placed at the origin of the (x_o,y_o) axis. In Figure 38 the tracking ship position was at x_o = +400 ft and y_o = +70. The interaction force −Y was almost zero during the time of this run, while the interaction moment −N had a positive value producing a positive yaw angle. Because $\dot{y}_o$ was positive the track of the leading ship reduced the lateral distance (β).

Similar discussion can be made for the response of Figure 39 where the tracking ship was placed at x_o = −400 feet and y_o = 70 feet. The lateral distance was again reduced continuously.

Several "stationary" runs, i.e. at the same speed of 15 knots for both the ships, were made for the longitudinal distance (α) being 160 ft, 300 ft, 200 ft and the lateral distance (β) 70 ft, respectively. Figures 40, 41, 42, 43, 44, 45 show these responses in terms of the perturbated parameters of the leading ship, ψ,Y,N,$\dot{y}_o$,α,β,

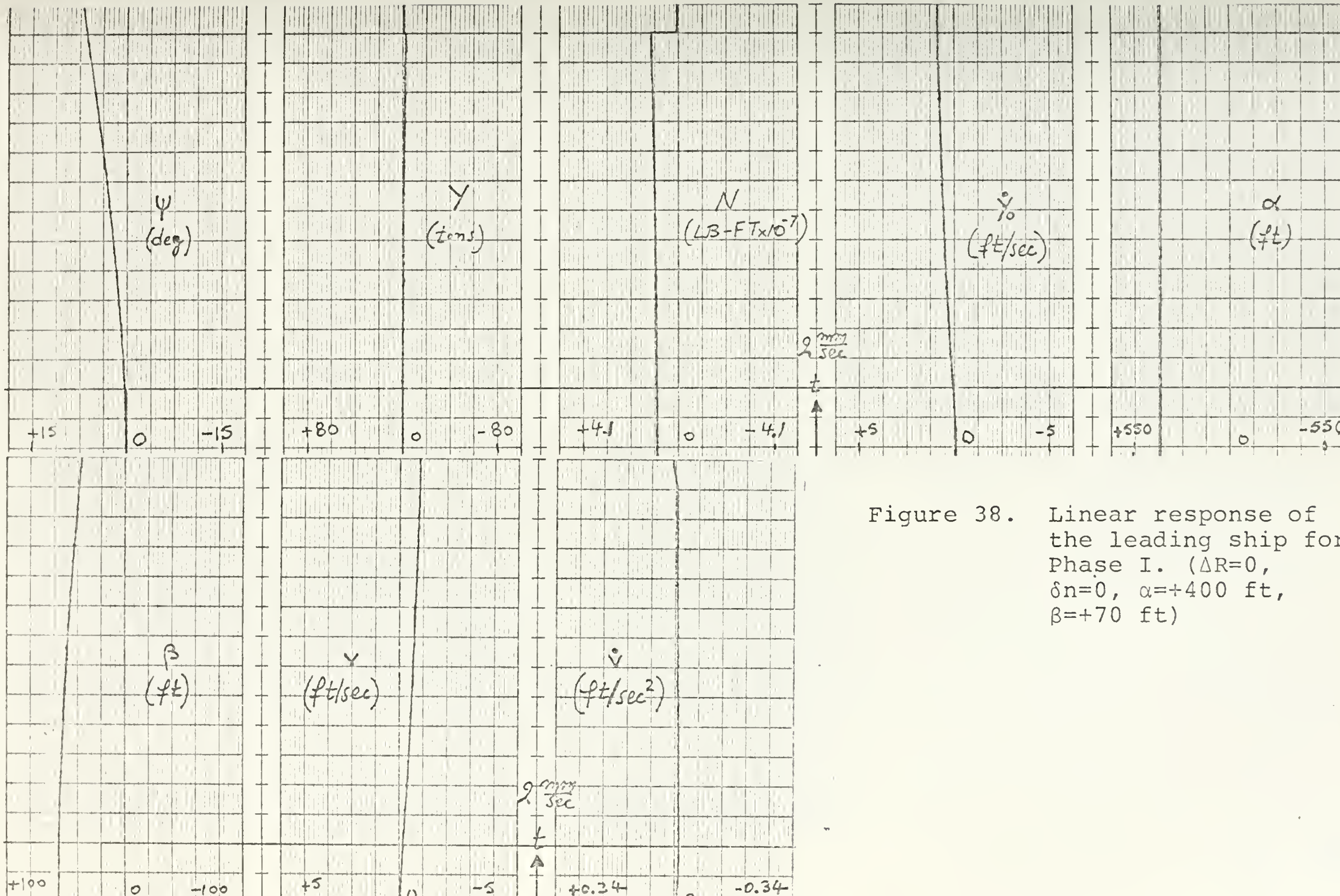


Figure 38. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=0$, $\alpha=+400$ ft, $\beta=+70$ ft)

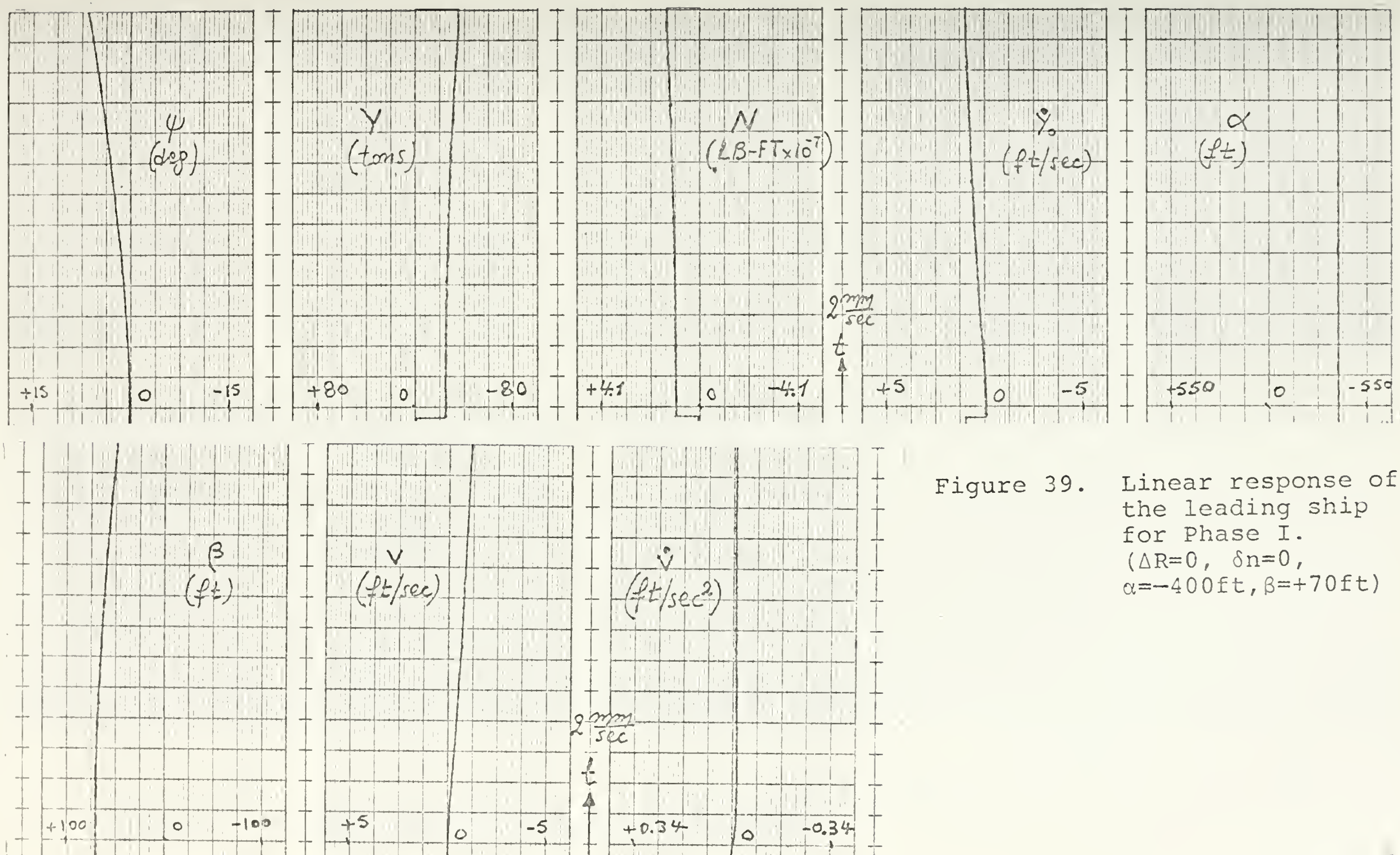


Figure 39. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=0$, $\alpha=-400$ft, $\beta=+70$ft)

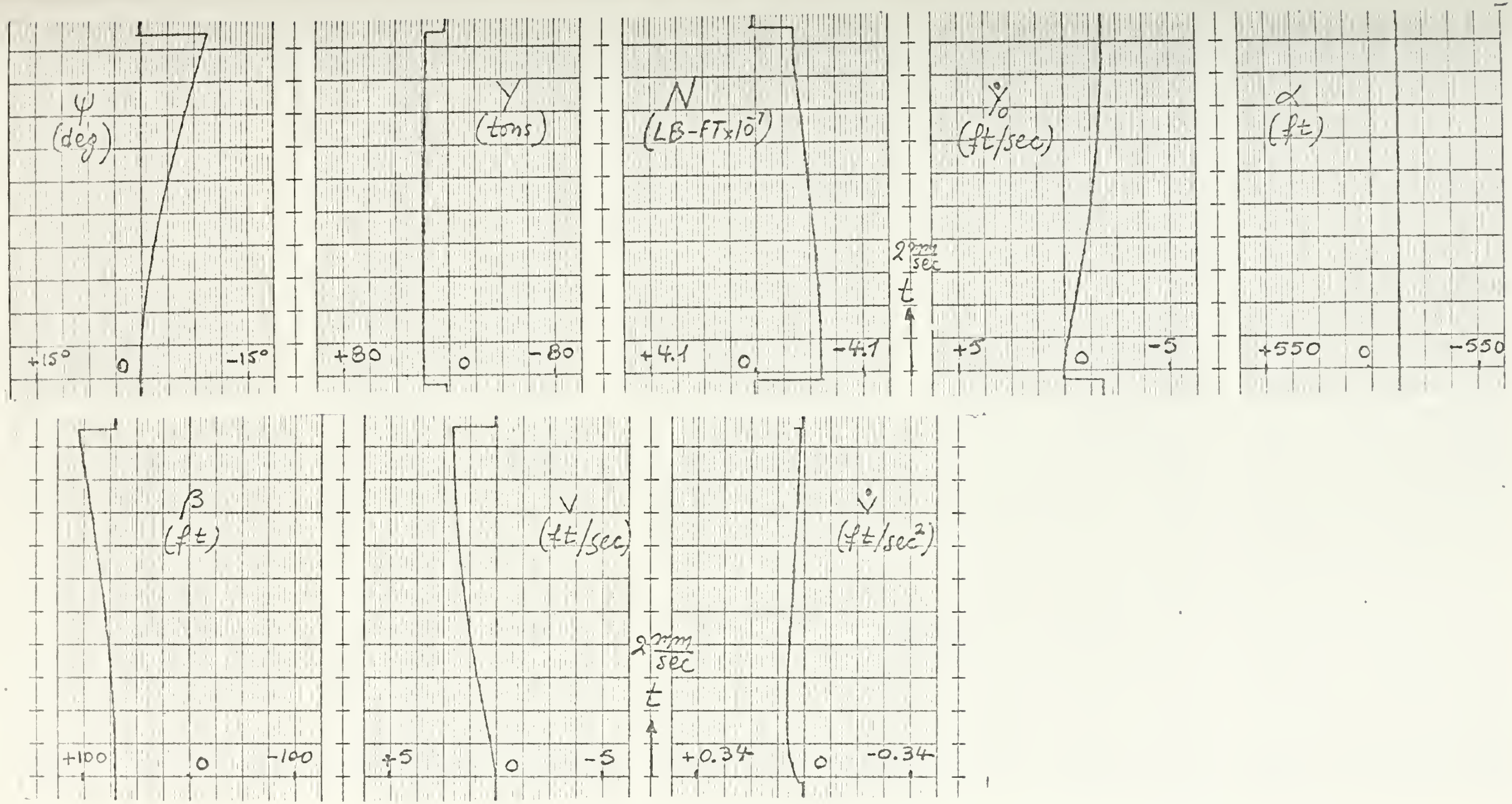


Figure 40. Linear response of the leading ship for Phase I.
($\Delta R=0$, $\delta n=0$, $\alpha= -160$ft, $\beta= +70$ft)

Figure 41–1. Linear response of the leading ship for Phase I.
($\Delta R=0$, $\delta n=0$, $\alpha=+160$ft, $\beta=+70$ ft)

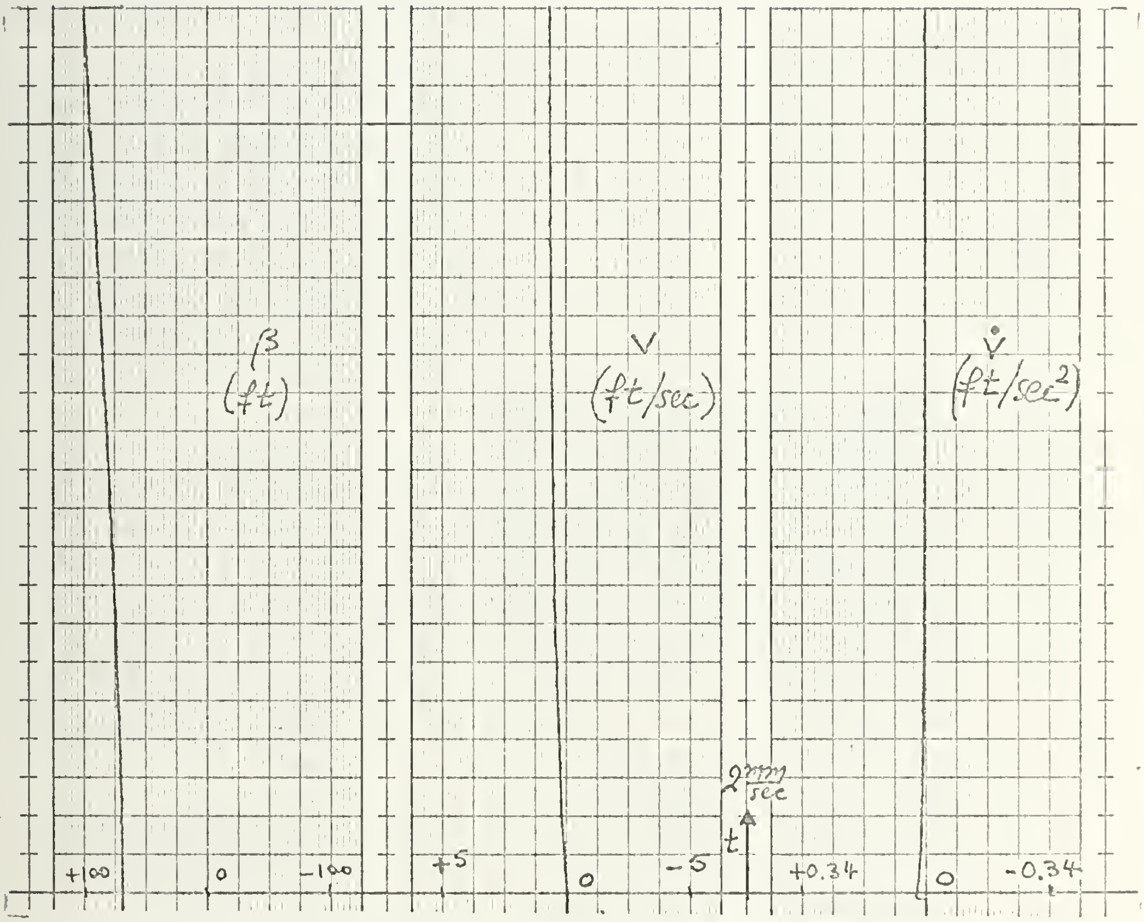


Figure 41–2. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=0$, $\alpha=+160ft$, $\beta=+70ft$)

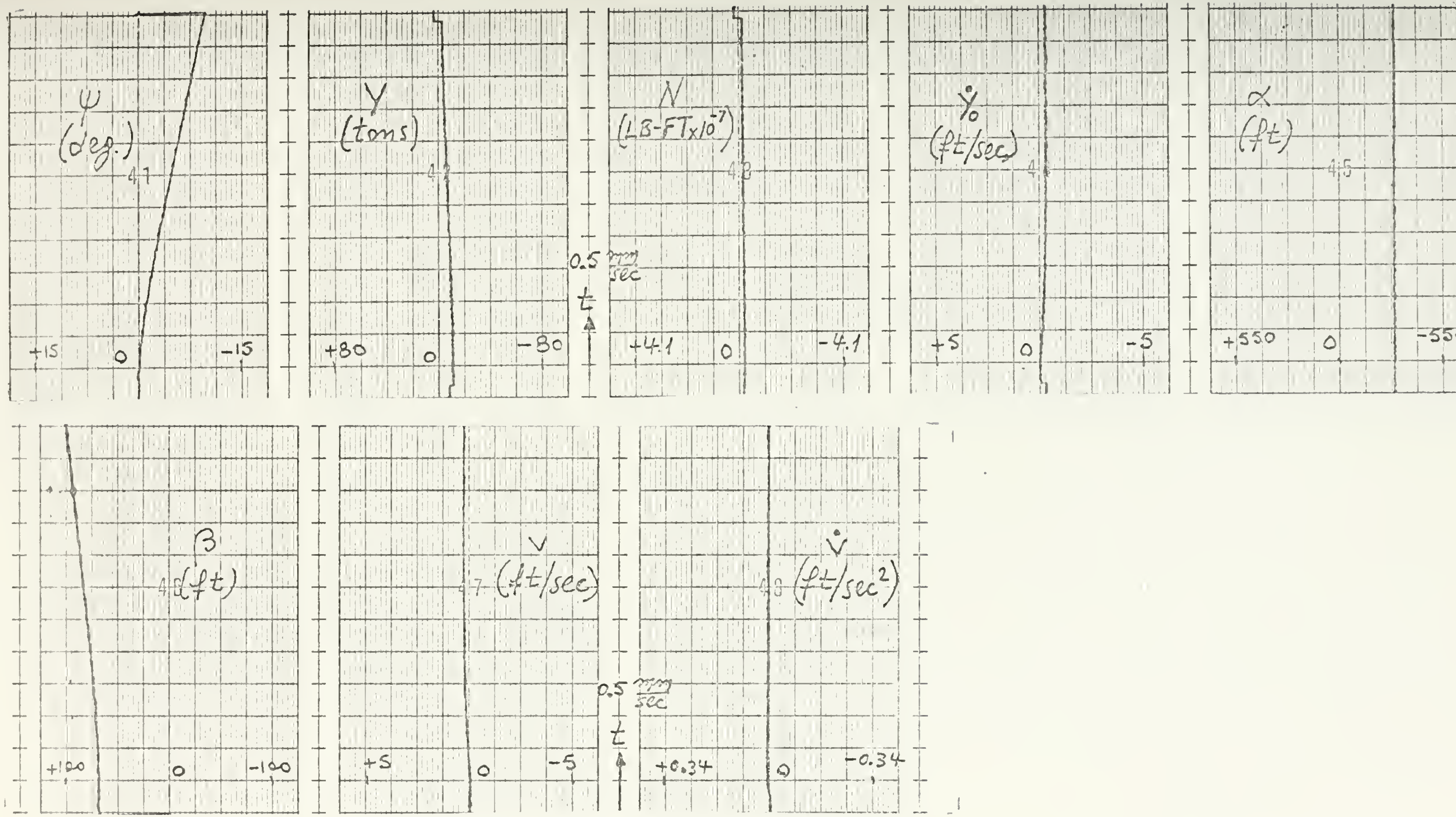


Figure 42. Linear response of the leading ship for Phase I.
($\Delta R=0$, $\delta n=0$, $\alpha=-300ft$, $\beta=+70ft$)

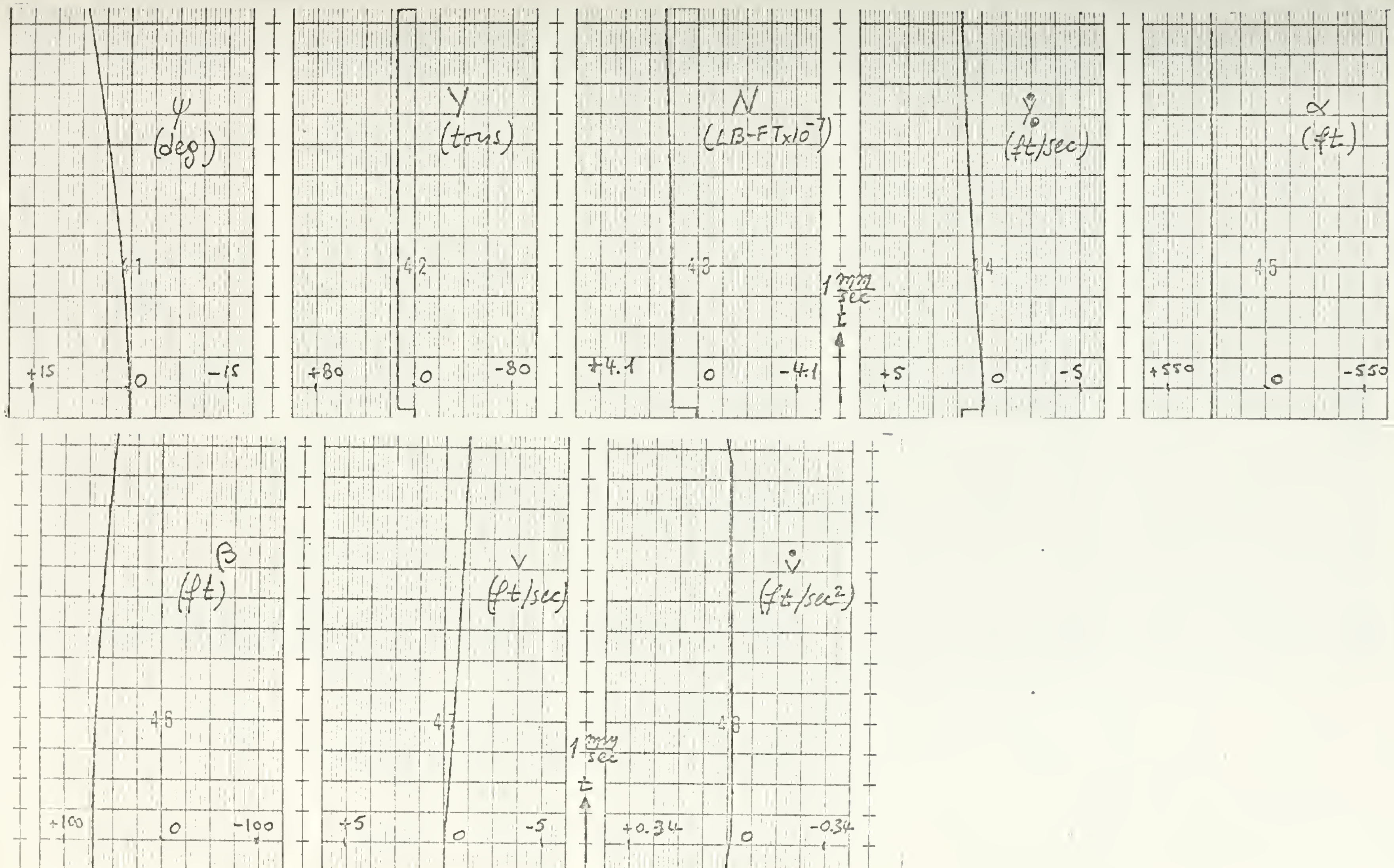


Figure 43. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=0$, $\alpha=+300$ft, $\beta=70$ ft)

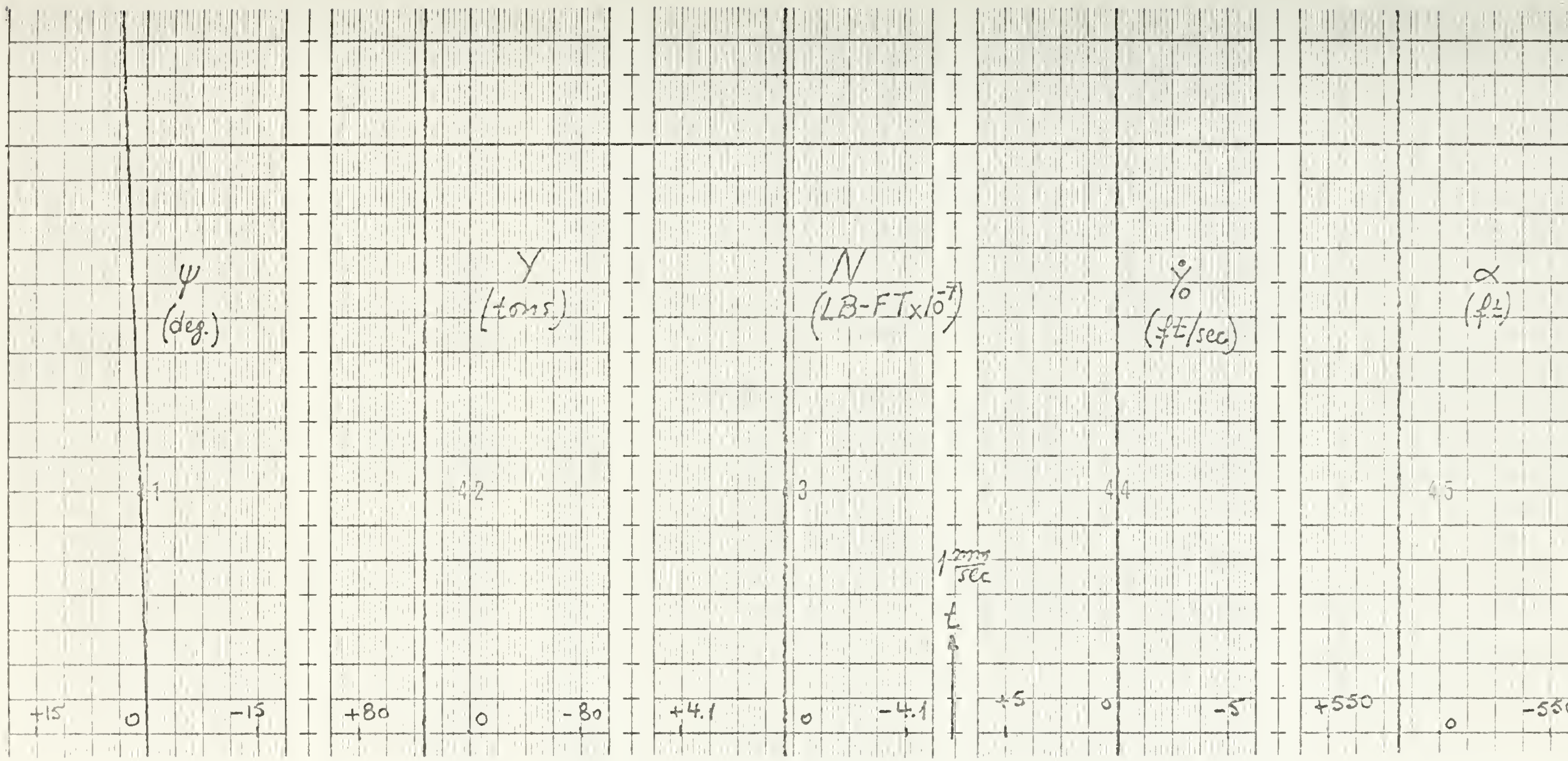


Figure 44—1. Linear response of the leading ship for Phase I.
(ΔR=0, δn=0, α=+200ft, β=+70ft)

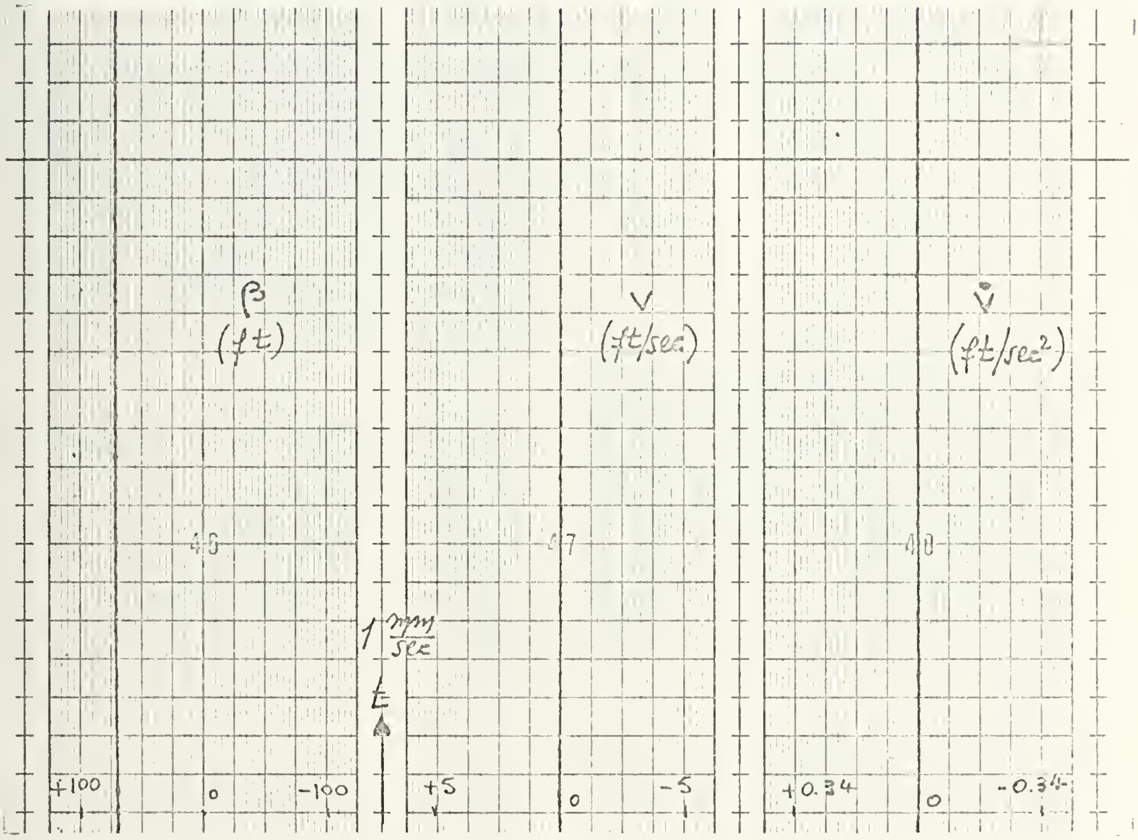


Figure 44-2. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=0$, $\alpha=+200ft$, $\beta=+70ft$)

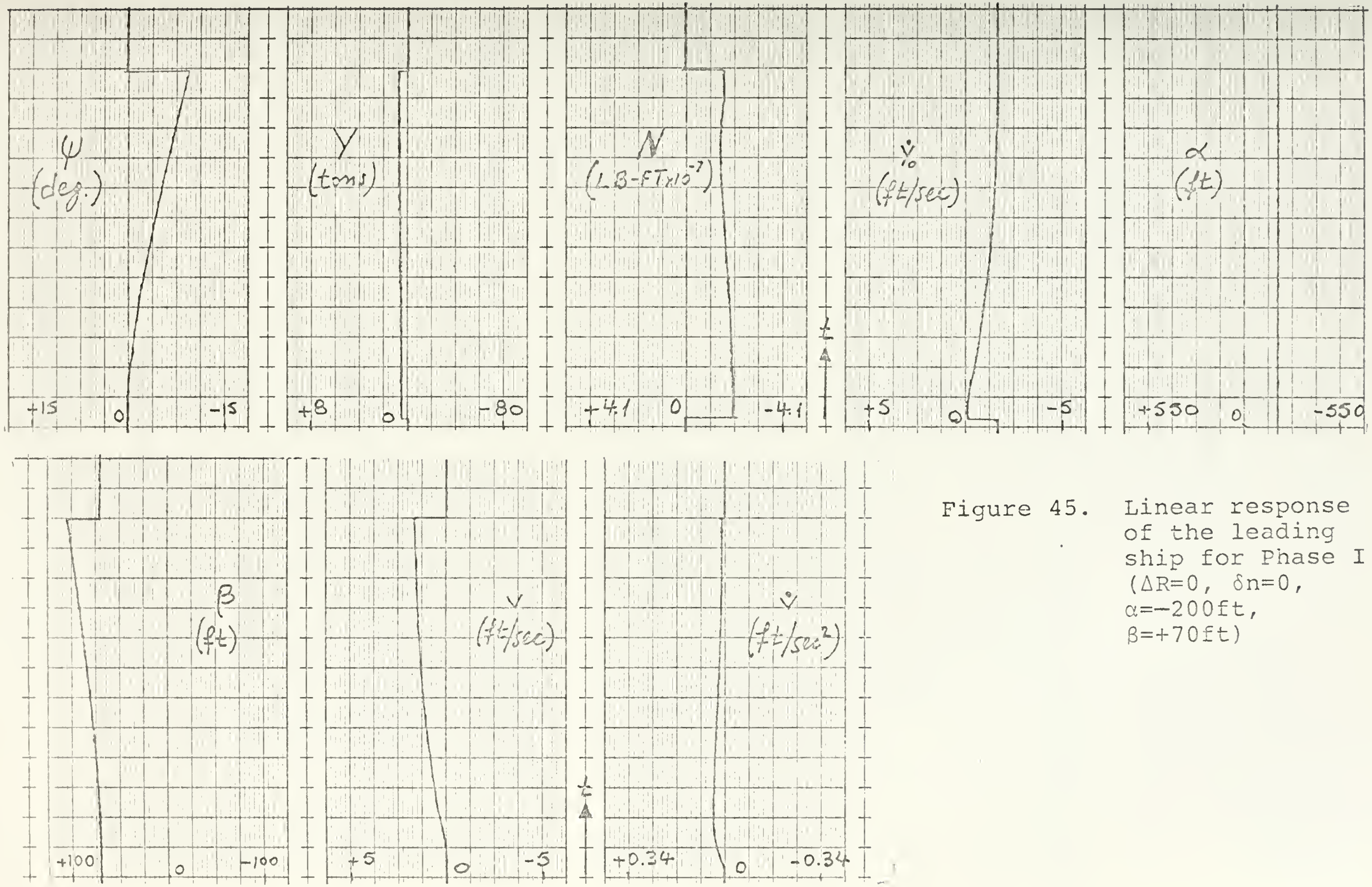


Figure 45. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=0$, $\alpha=-200$ft, $\beta=+70$ft)

$v, \dot{v}$. The analysis of these response curves is analogous to the previous ones. The lateral distance in some cases is reduced and others increased by the interaction effects depending on the relative longitudinal position of the ships since the lateral distances were kept constant at 70 ft at the beginning of each run.

From the observation of these "stationary" runs it seems that, there are positions where both the interaction force and moment acting on the leading ship tend to draw the leading ship towards the tracking ship. Such positions seem to be at the longitudinal distances of 524 ft, 400 ft and 300 ft.

An interesting effect was observed when the longitudinal distance is +200 ft and the lateral distance +70 ft, Figure 44. Although the interaction force-Y and moment-N had both positive values they did not affect the lateral distance (β) throughout the time of the run (2 minutes roughly) because the interaction effects counteracted each other, due to the fact that the positive interaction moment was producing a yaw positive angle such as to counteract the positive interaction force. The the $\dot{y}_o$ velocity of the leading ship was zero in this case and so the lateral distance could be kept constant. At this point for the ease of the manual control the input voltage into the steering control block and into the propeller speed blcok is changed as Figure 46 shows for ship model No 1 and Figure 47 shows for ship model No 2.

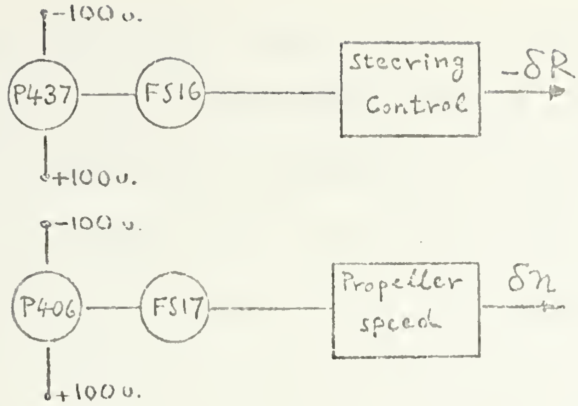


Figure 46. Rudder and propeller input commands diagrams for ship model No 1.

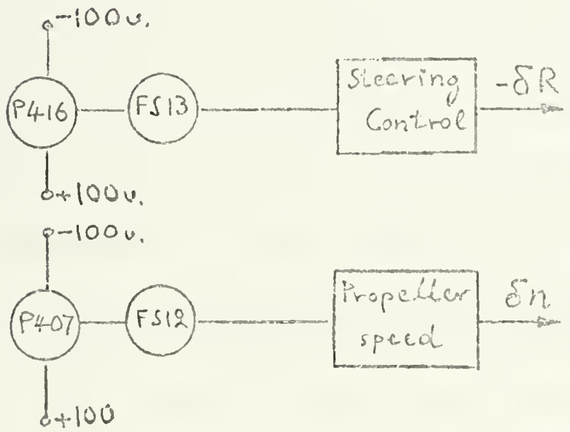


Figure 47. Rudder and propeller input commands diagrams for ship model No 2.

Those analog configurations shown on Figures 46 and 47 for both ship models respectively replace the up till now used configuration. This is done primarily because one can have negative or positive rudder and propeller speed changes without necessarily changing the switch position. This obviously gives operative flexibility for the operator making the control of the ship more realistic besides the necessary required sensitivity of the rudder

wheel and propeller. Then for zero rudder or propeller speed change either the corresponding switch has to be open or the corresponding potentiometer has to be set at 0.5000 value. For example for the rudder angle will be 5 turns for 0 to 20° and 5 turns 0 to −20° which corresponds to 4° per turn. Likewise it will be 5 turns for 0 to ± 30 RPM hence it will correspond to 6 RPM per turn. For the ease of operation the potentiometer values for P437, P406, P416, P406 should be set in "RESET" mode having in mind that 100.0 volts corresponds to 20° rudder and 30 RPM of propeller speed respectively. This avoids the confusion of converting in "POTSET" mode the potentiometer values to be set in actual volts since now the 0.5000 position of the potentiometers corresponds to zero volts.

b. Runs with different propeller speed between ship A (leading ship) and ship B(tracking ship)

Two kinds of runs were made, one with the tracking ship have a speed of +10 RPM greater than the speed of 15 knots of the leading ship. In the second run the difference in propeller speed was 5 RPM. Note that no controls were applied. The following assumption was made: both ships can be placed at any desired initial position at the beginning of the run. This was done because no complete run with the tracking ship passing the leading ship was possible to be made primarily for two reasons:

(1) Saturation effects of the analog computer amplifiers.

(2) Interaction effects can be applied only for the lateral distance being between 50 ft and 100 ft.

This assumption holds for Phase II also. A matter of future investigation would be a rescaling of the analog computer unit to avoid the saturation effects. Also more data should be available for the interaction effects to be applied for lateral distances outside, the range of 50 to 100 ft. Nevertheless the tracking ship was placed at different initial longitudinal distances from −524 ft to +524 ft. All the responses of the leading ship for Phase I were calculated in terms of the perturbated parameters of the leading ship $\psi, Y, N, \dot{y}_o, \alpha, \beta, v, \dot{v}$. From the observations of the obtained responses, Figure 48 to Figure 64, it can be seen that during the approach and the departure of the tracking ship the leading ship tends to reduce the lateral distance, β. So a possibility of collision appears. More specifically the tracking ship starts at −524 ft longitudinal distance with 10 RPM propeller speed greater than that of 15 knots and tries to overtake the leading ship, Figure 48. Due to interaction moment N the leading ship yaws to a positive angle and so tends to reduce the lateral distance, β, although the interaction force Y is negative. In Figure 49, the next run, the tracking ship starts to overtake the leading ship at a longitudinal distance of −400 ft with 10 RPM propeller speed greater than that of the leading ship. It can be seen that originally the yaw angle is positive due to the positive interaction moment and the lateral distance is decreasing again. This in fact

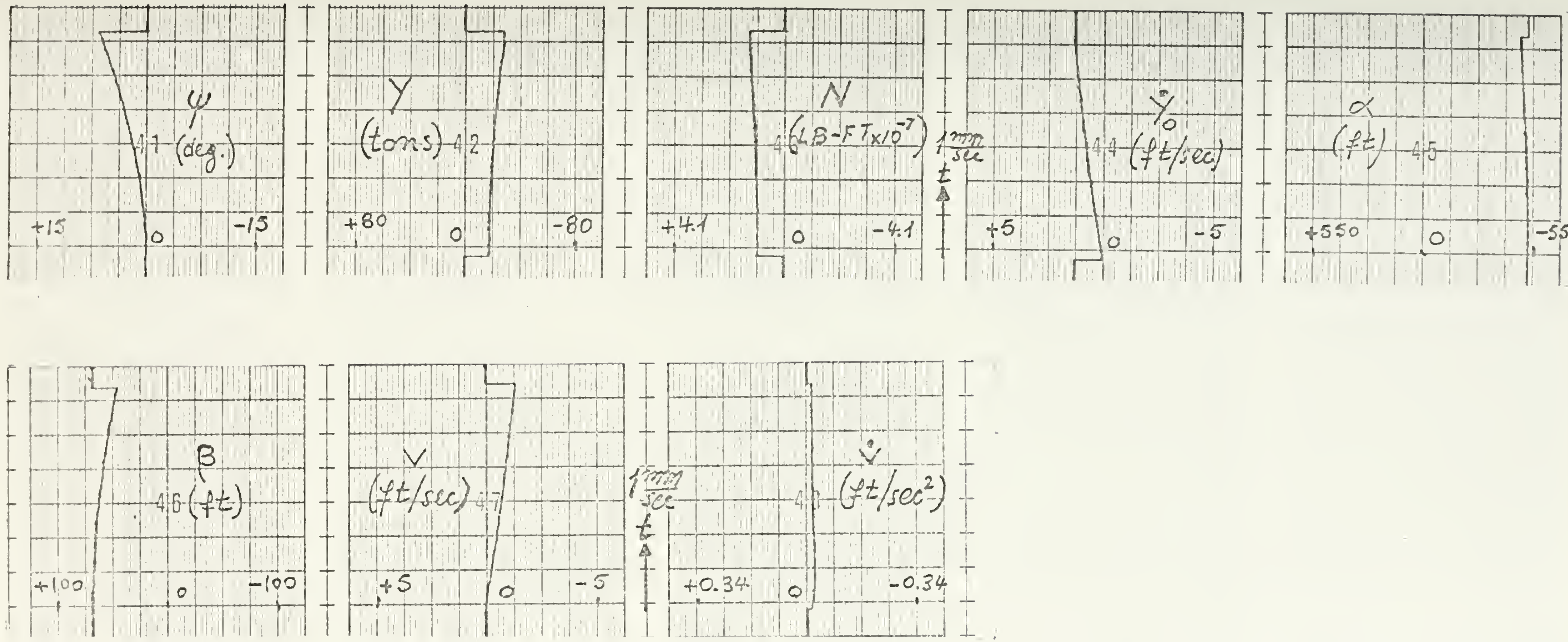


Figure 48. Linear response of the leading ship for Phase I. (ΔR=0, δn=+10 RPM, initially α=−524ft, β=70ft)

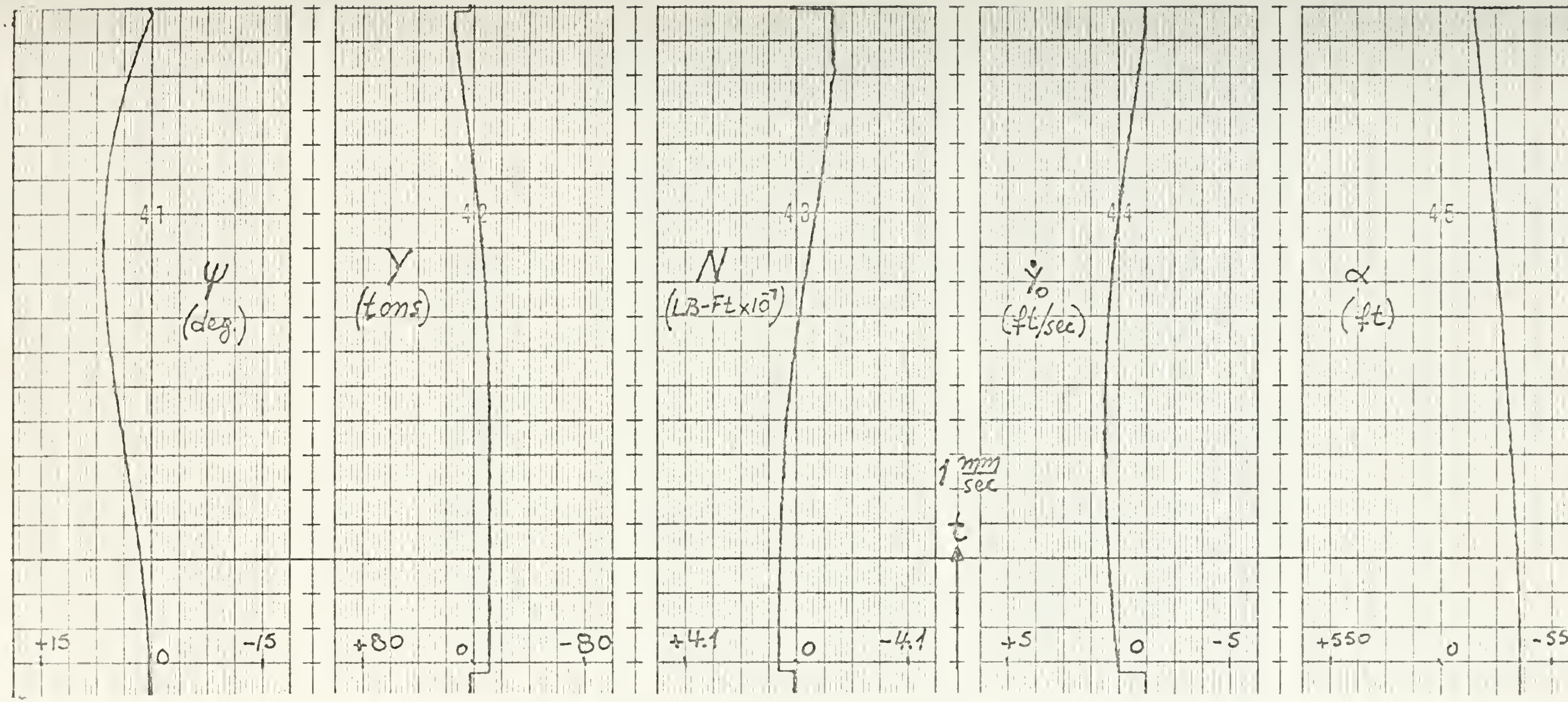


Figure 49–1. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=-400$ft, $\beta=100$ft)

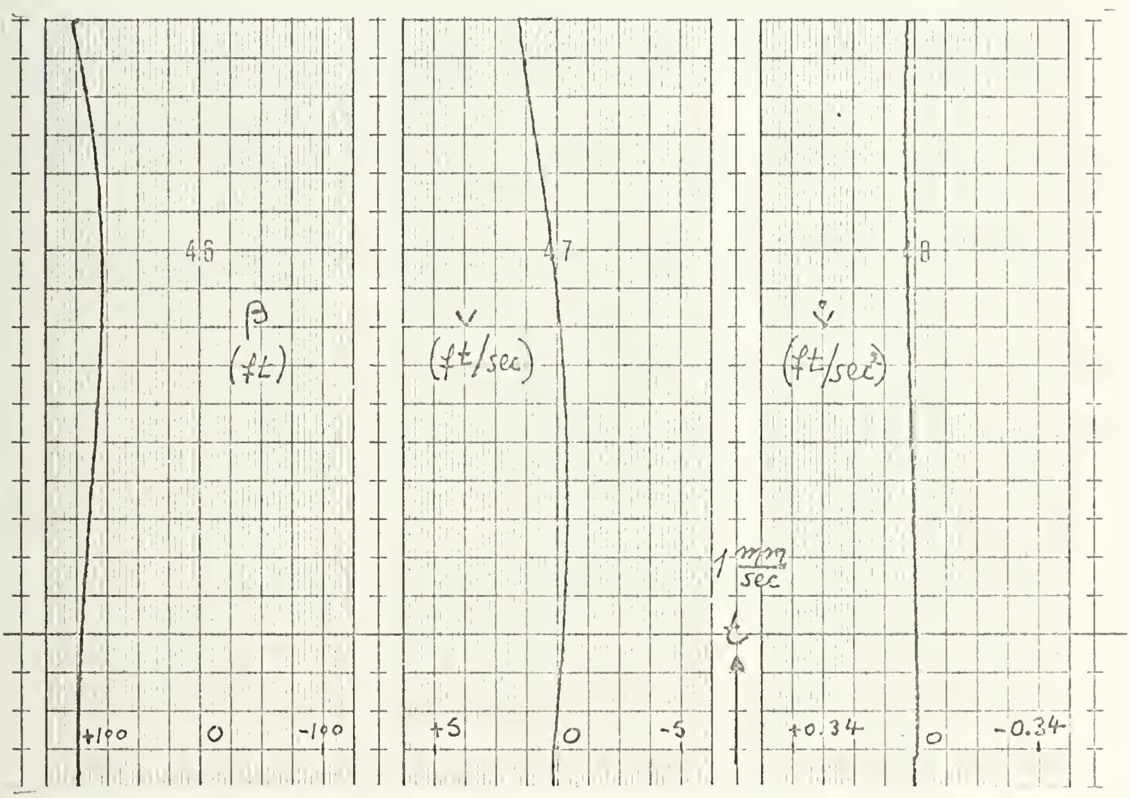


Figure 49. Linear response of the leading ship for Phase I (ΔR=0, δn=+10 RPM, initially α=−400ft, β=100ft)

is happening because the bow of the leading ship yaws towards the oncoming tracking ship. When the longitudinal distance is reduced to −200 ft the leading ship starts to yaw at a negative angle; this is because both the Y-force and N-moment changed sign, hence the lateral distance being unchanged for about 15 sec at 50 ft approximately, starts to increase toward 100 ft when the longitudinal distance is approximately 160 ft.

In the next shown run, Figure 50, similar analysis can be made except from the fact that the tracking ship now starts at initial position at $x_o = -300$ ft and $y_o = +50$ ft. The lateral distance being 50 ft for about 15 sec starts to increase when the longitudinal distance is approximately −200 ft.

Figure 51 shows the response for an initial position of the leading ship at (0,0) and the tracking ship at (0,50 ft). The tracking ship possesses a 15 RMP greater propeller speed than that of 15 knots. The leading ship immediately starts to yaw negatively and thus increases the lateral distance drastically.

In Figure 52, where initially $\alpha = +160$ ft and $\beta = 70$ ft it is seen that the lateral distance increases until the longitudinal distance is +200 ft. Then due to the interaction effects the leading ship reduces the lateral distance, since a positive $\dot{y}_o$ velocity has been created.

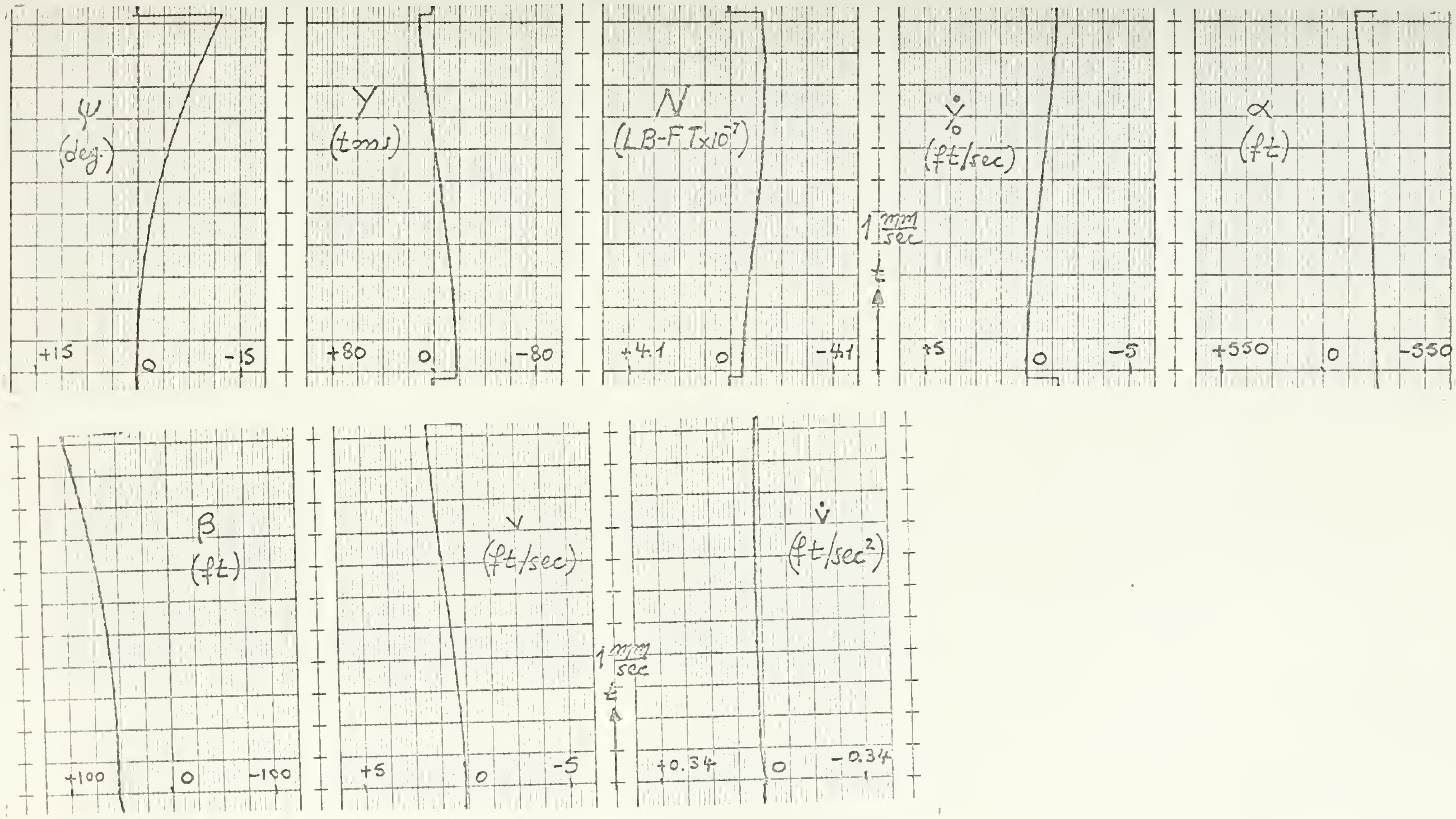


Figure 50. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=-300$ft, $\beta=50$ft)

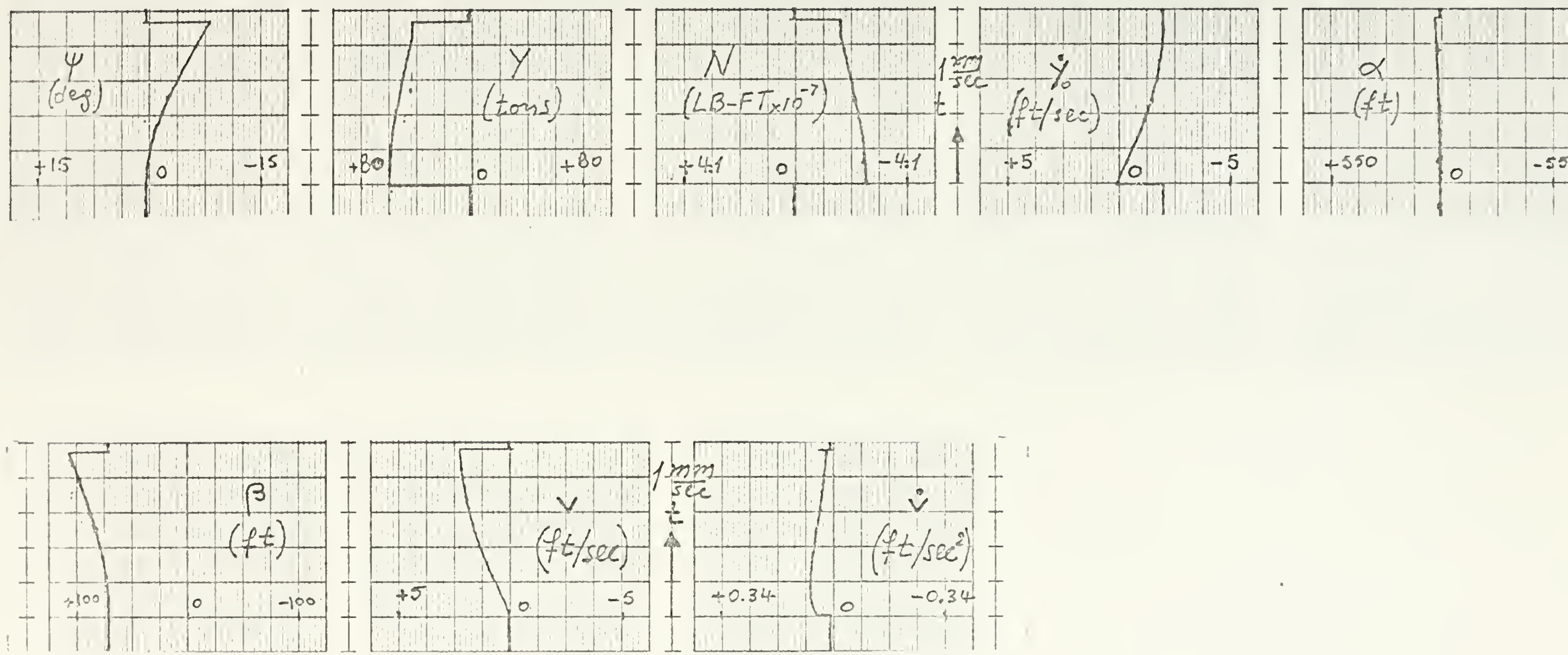


Figure 51. Linear response of the leading ship for Phase I.
($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=0$, $\beta=50$ft)

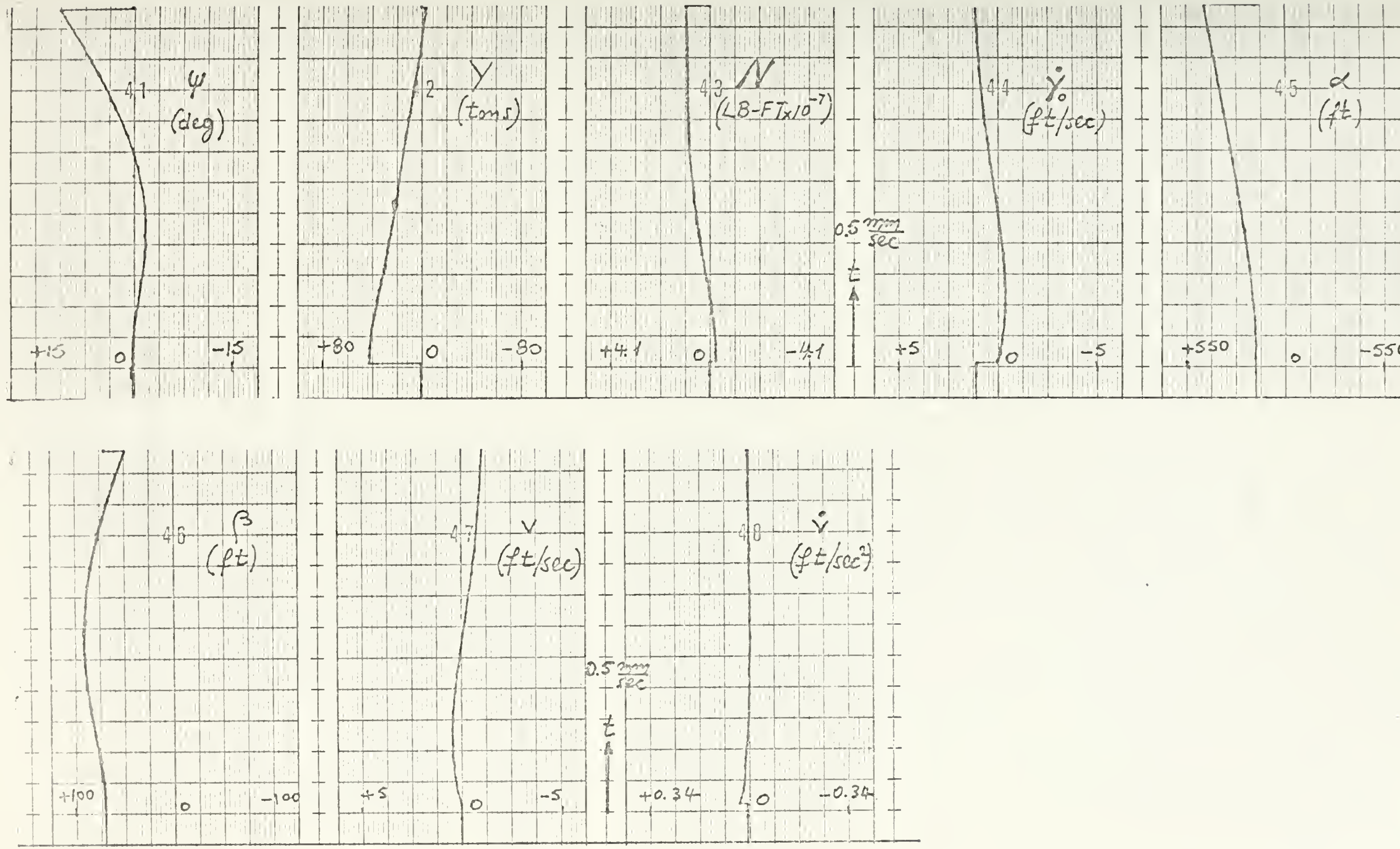


Figure 52. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=+160$ft, $\beta=70$ft)

Figures 53, 54, 55 show the response of the leading ship when α and β were initially set at +300 ft, +400 ft, +524 ft, and 70 ft respectively, at 5 RPM difference in propeller speed. It seems that the best position for two ships of the same size is exactly abeam when alongside. The increase of the lateral distance when the longitudinal distance is between approximately −200 ft and +200 ft implies that the leading ship yaws. Hence control has to be applied for it to keep a constant course. It is also obvious that the approach and departure of the tracking ship implies the use of control on the leading ship in order for it to avoid collision.

Figures 56 till 64 show the linear response of the leading ship for different initial positions of the tracking ship with a difference of 5 RPM in propeller speed. The tracking ship overtakes the leading ship, which has a 15 knots speed. A similar analysis can be made for these responses as was done for the previously mentioned runs.

4. Obtained Responses for Phase II

Computer Program VI shows the source deck used for Phase II. In Phase II interaction forces and moments are applied on both ships. The circuitry of both Figures 33a and 33b is used. It should be mentioned here that the digital machine computes for the leading ship the interaction force and moment corresponding to those longitudinal distance, α, and lateral distance, β, which the analog computer passes through the trunk lines to the digital computer.

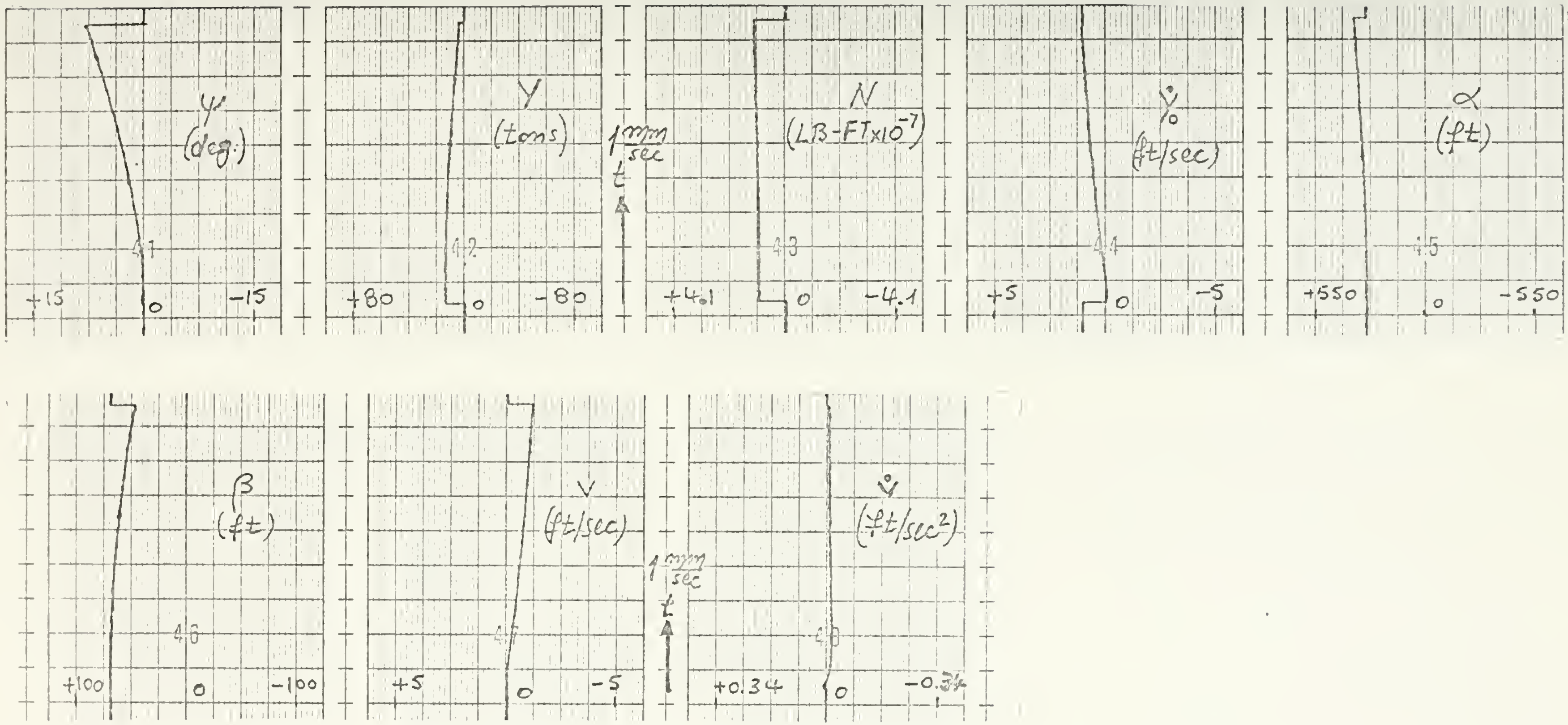


Figure 53. Linear response of the leading ship for Phase I. (ΔR=0, δn=+10 RPM, initially α=+300ft, β=70ft)

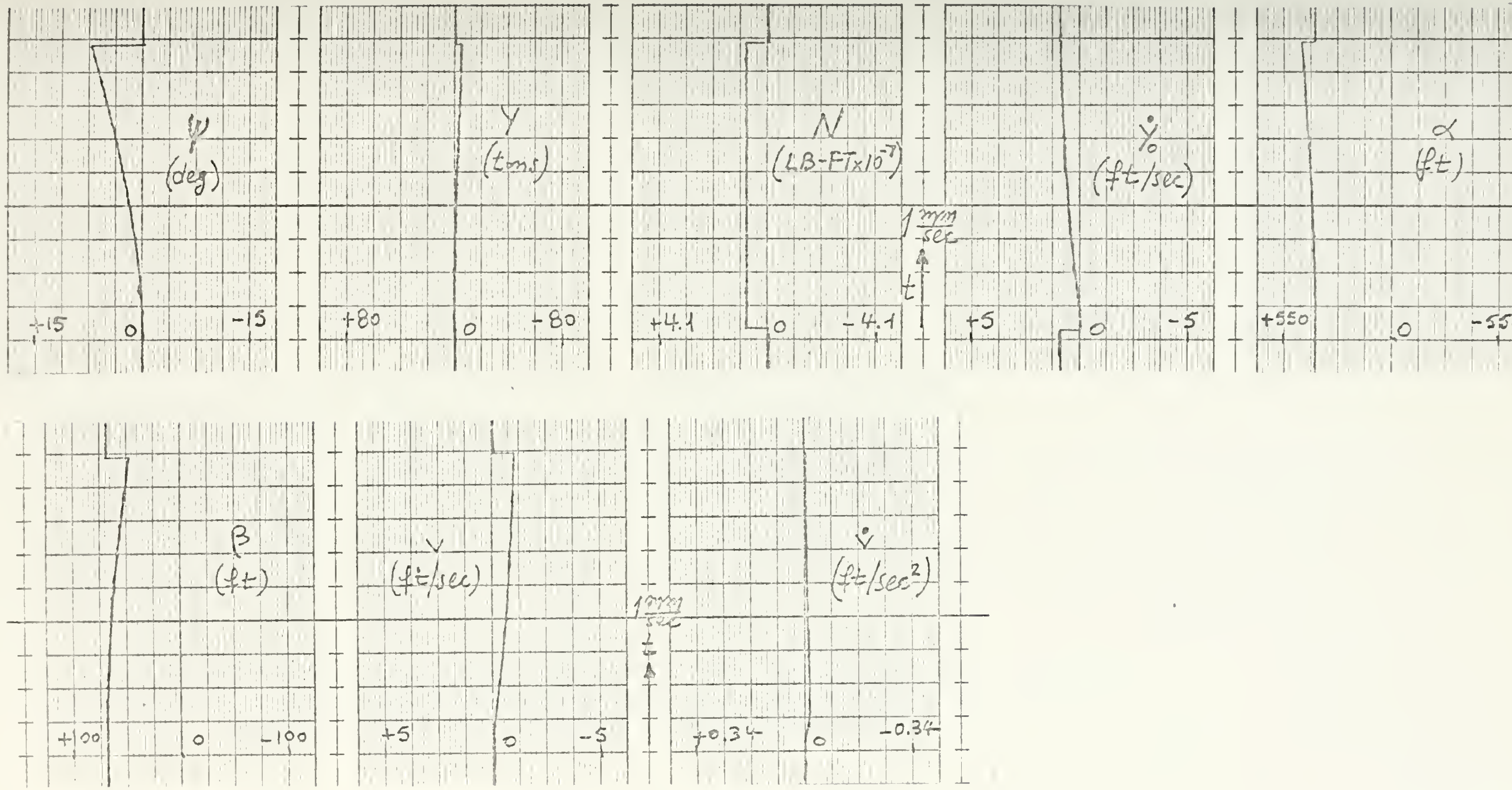


Figure 54. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=+400$ft, $\beta=70$ft)

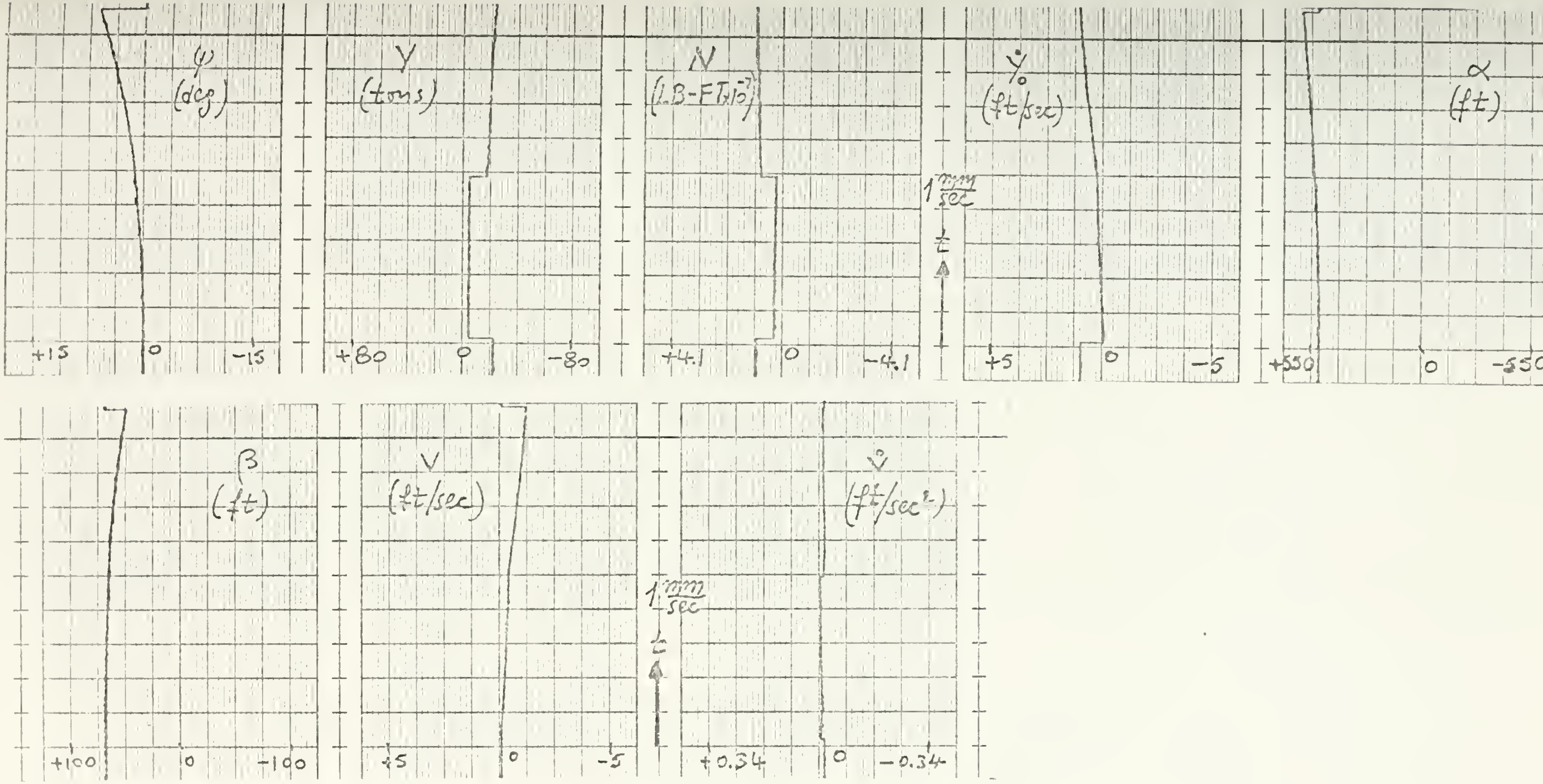


Figure 55. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=+524$ft, $\beta=70$ft)

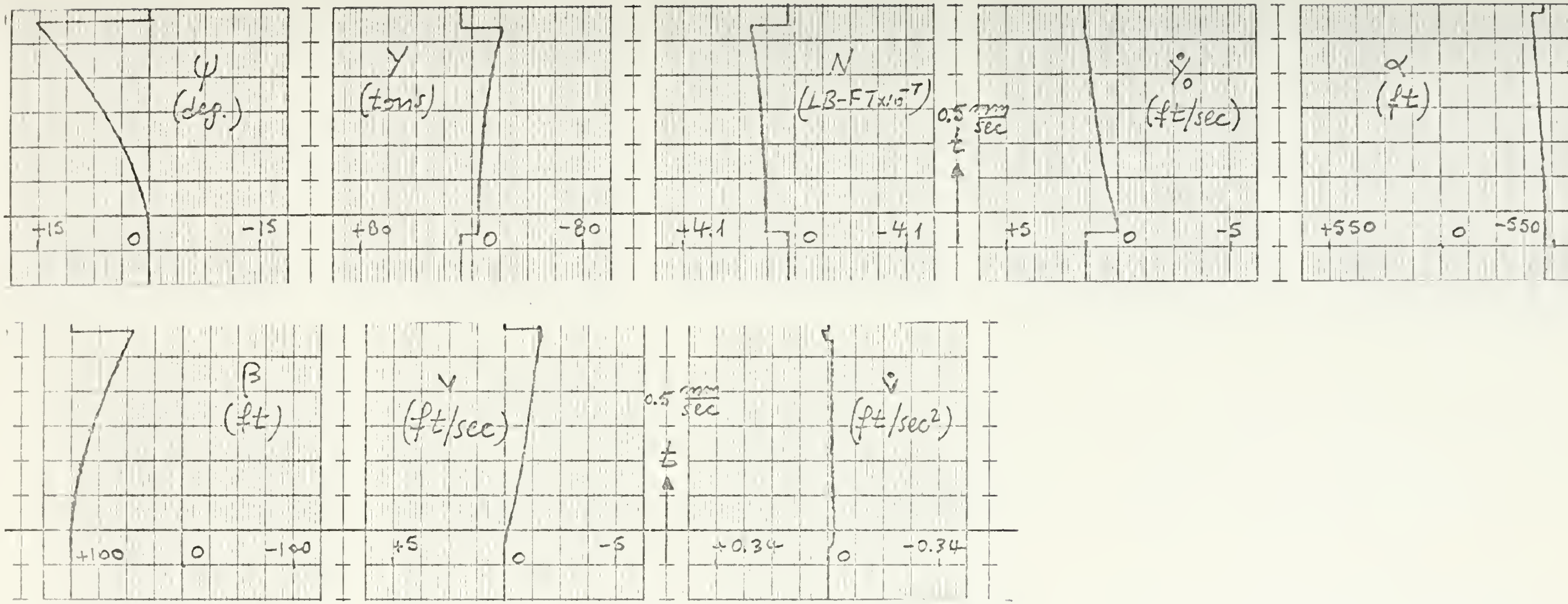


Figure 56. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=-524$ft, $\beta=100$ft)

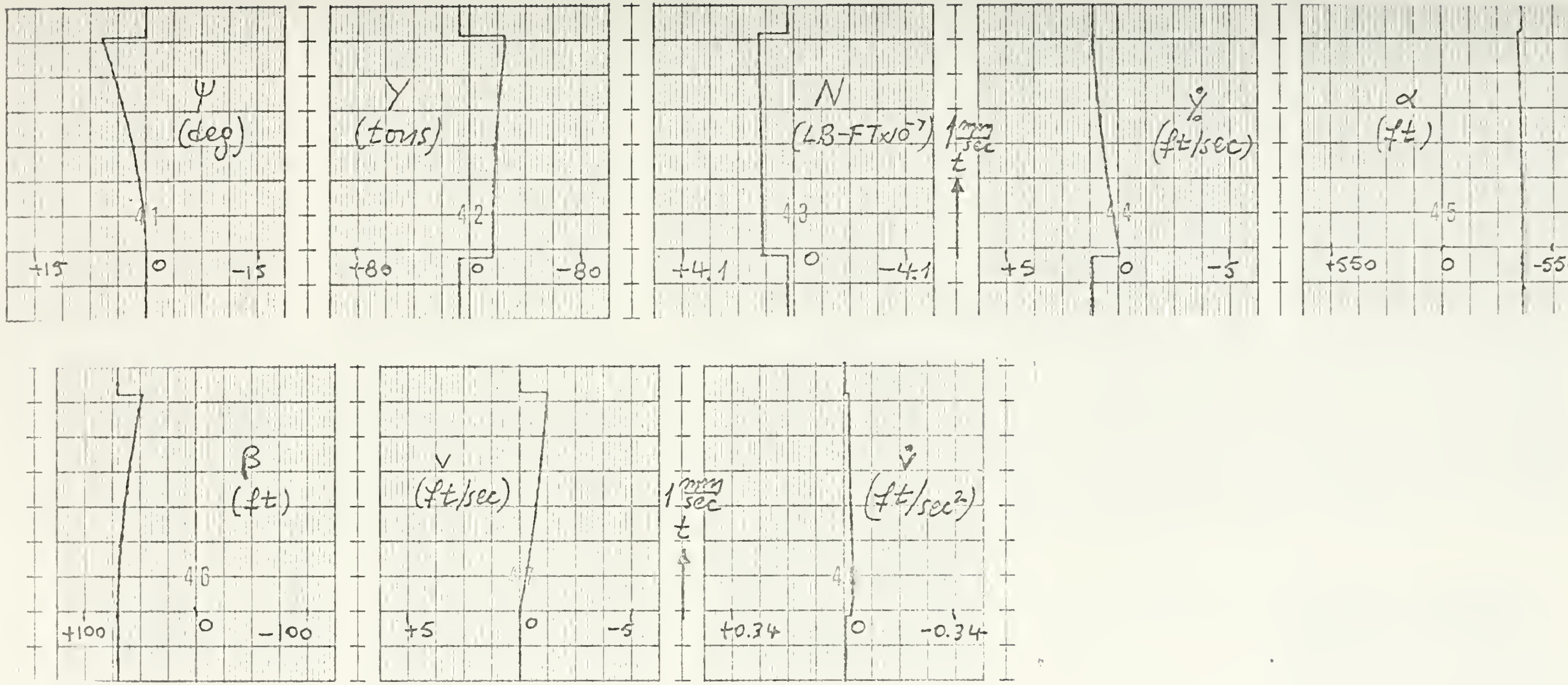


Figure 57. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=-400$ft, $\beta=70$ft)

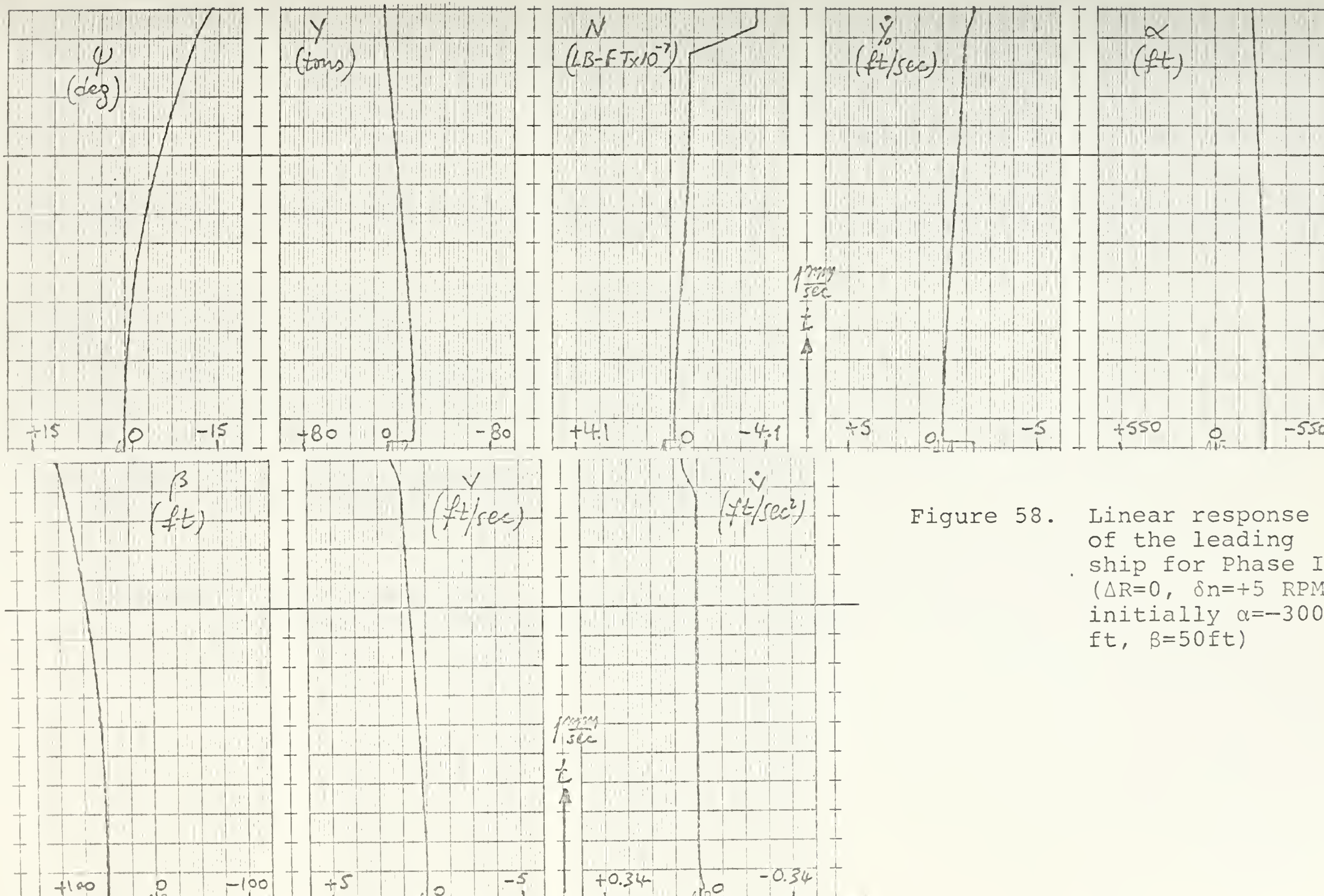


Figure 58. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=-300$ ft, $\beta=50$ft)

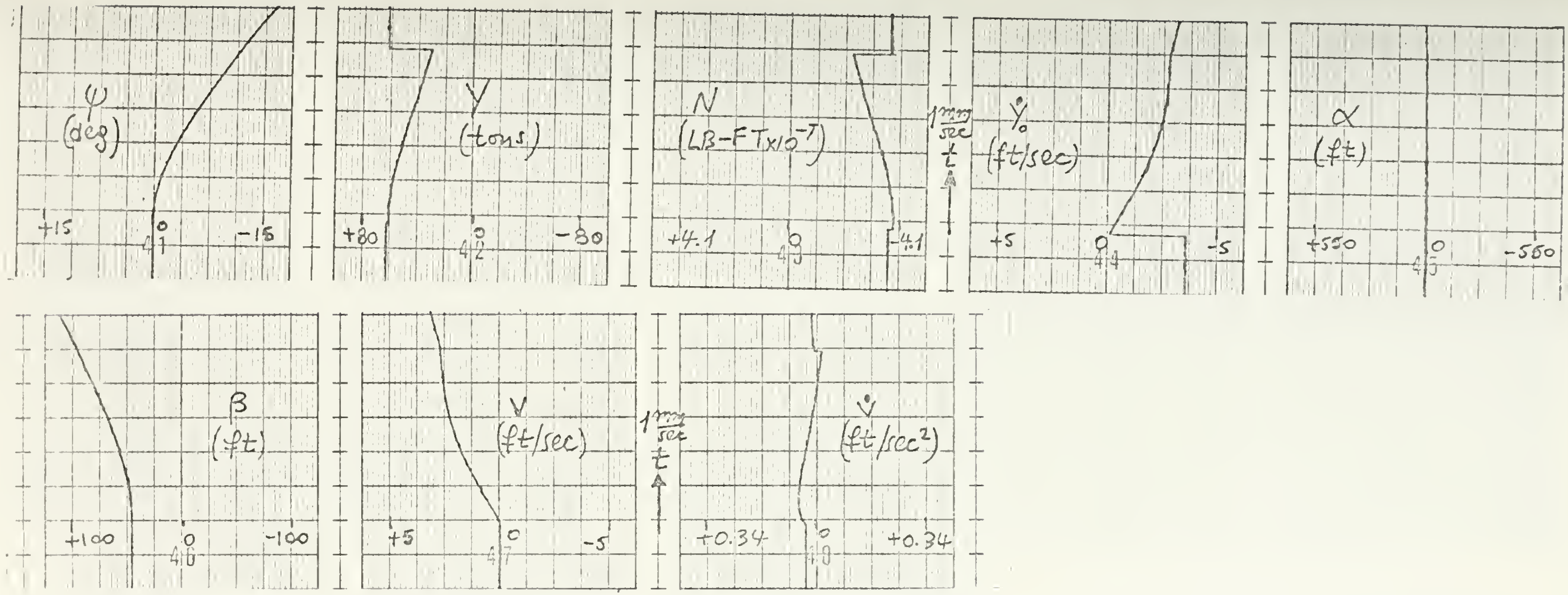


Figure 59. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=0$, $\beta=50$ft)

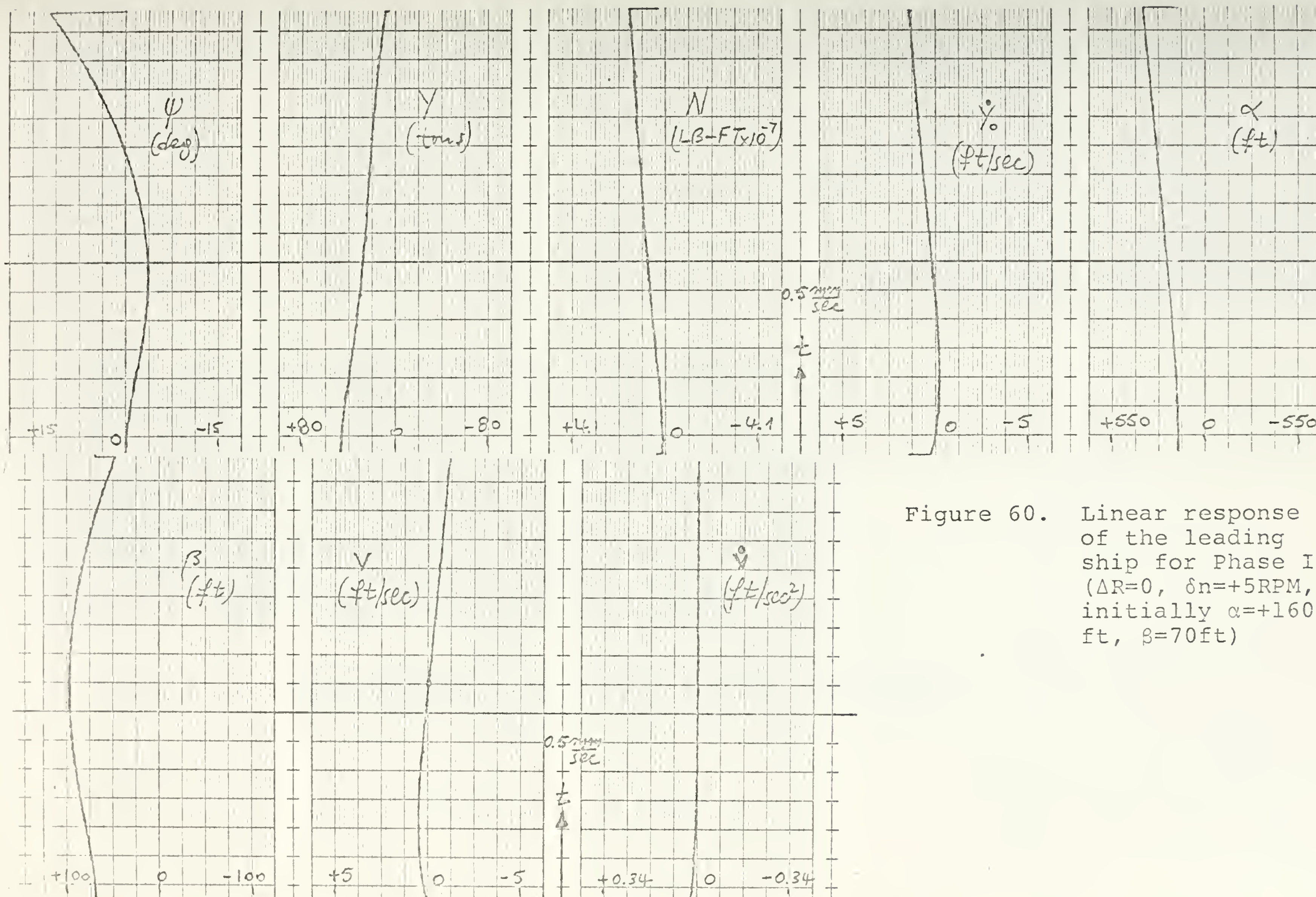


Figure 60. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+5$RPM, initially $\alpha=+160$ ft, $\beta=70$ft)

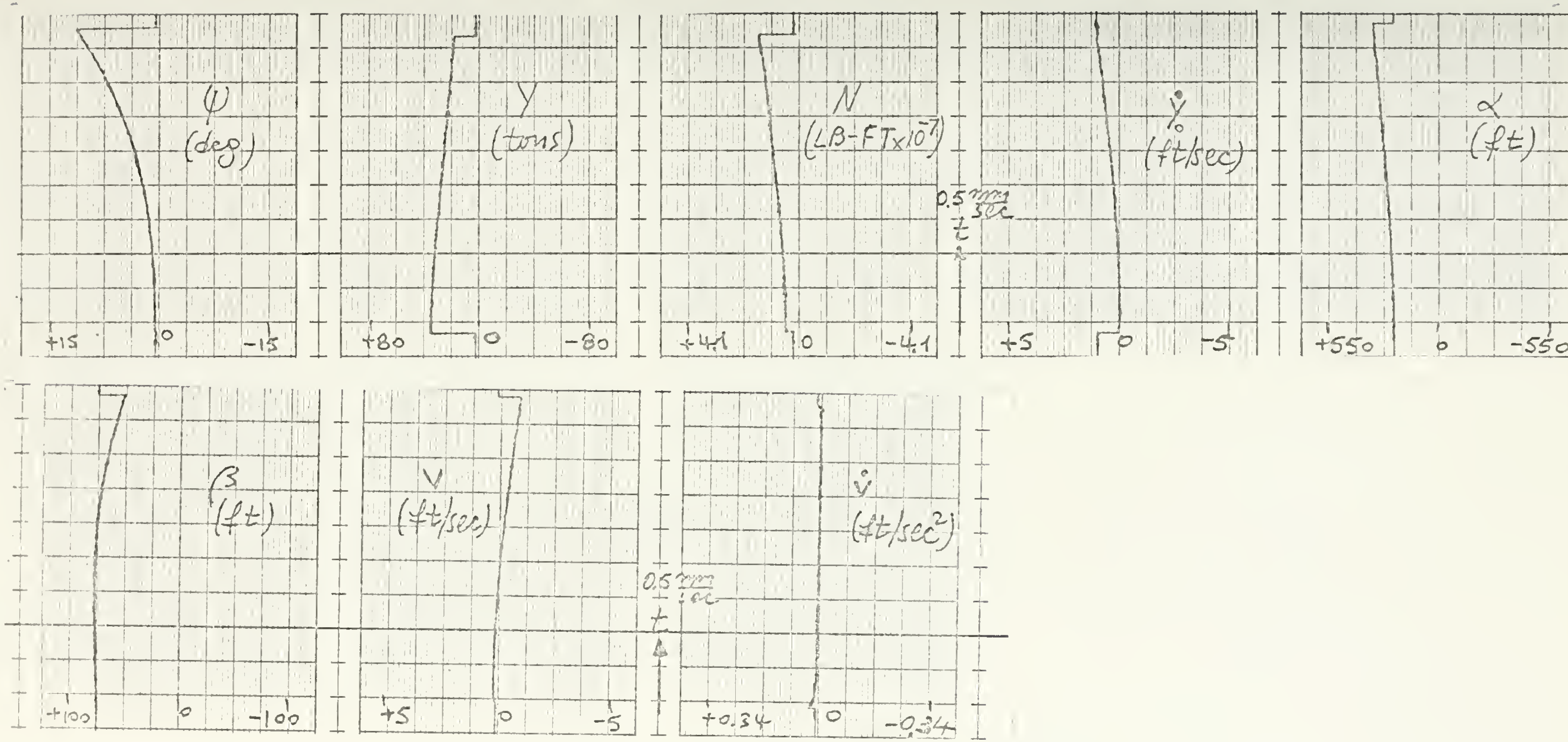


Figure 61. Linear response of the leading ship for Phase I.
($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+200$ft, $\beta=70$ft)

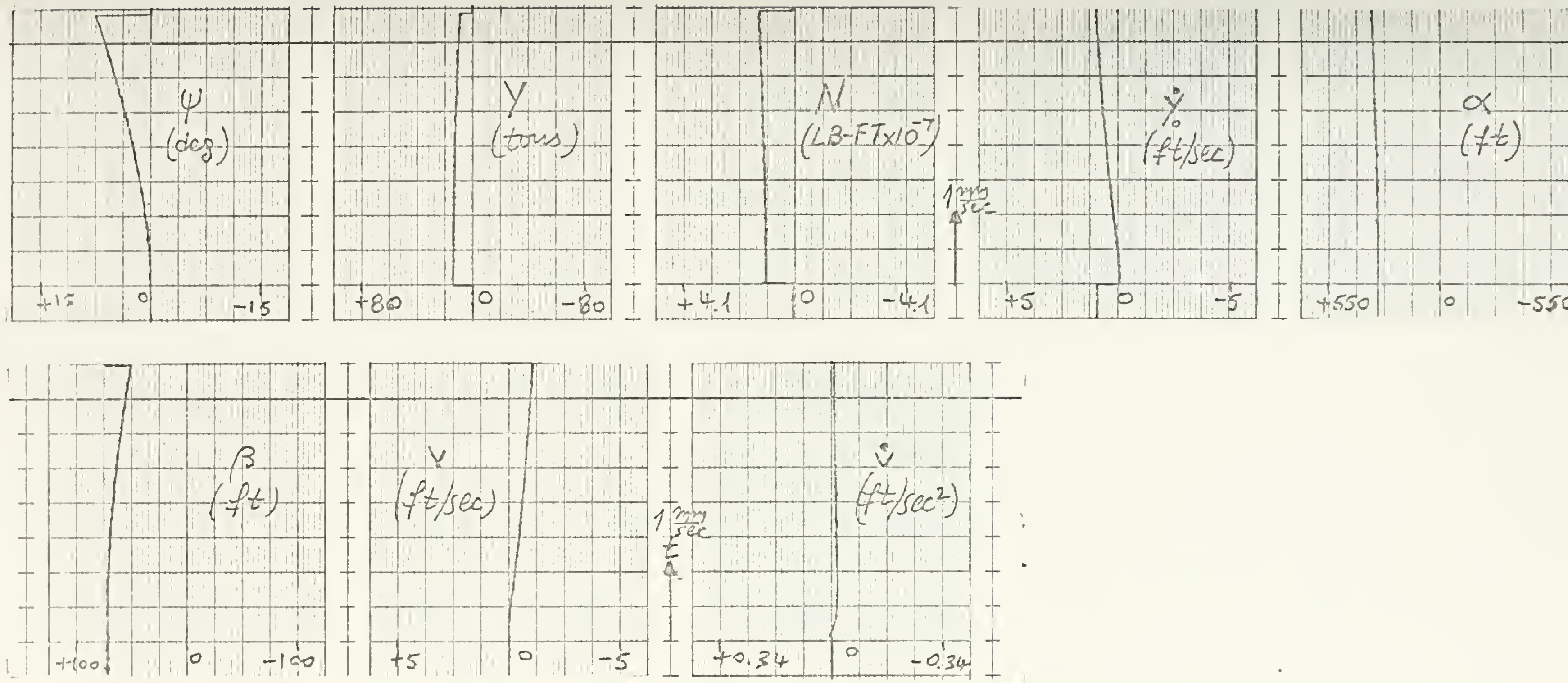


Figure 62. Linear response of the leading ship for Phase I.
(ΔR=0, δn=+5 RPM, initially α=+300ft, β=70ft)

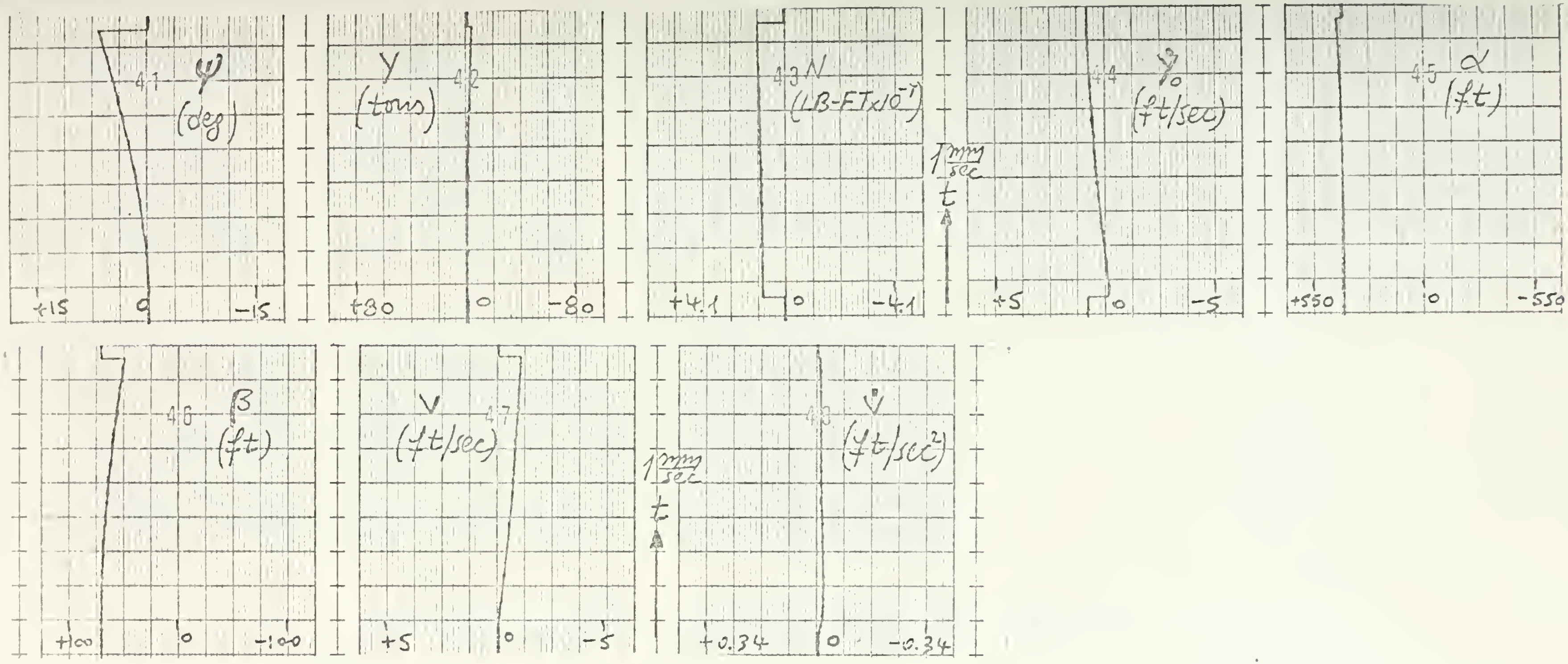


Figure 63. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+400$ft, $\beta=70$ft)

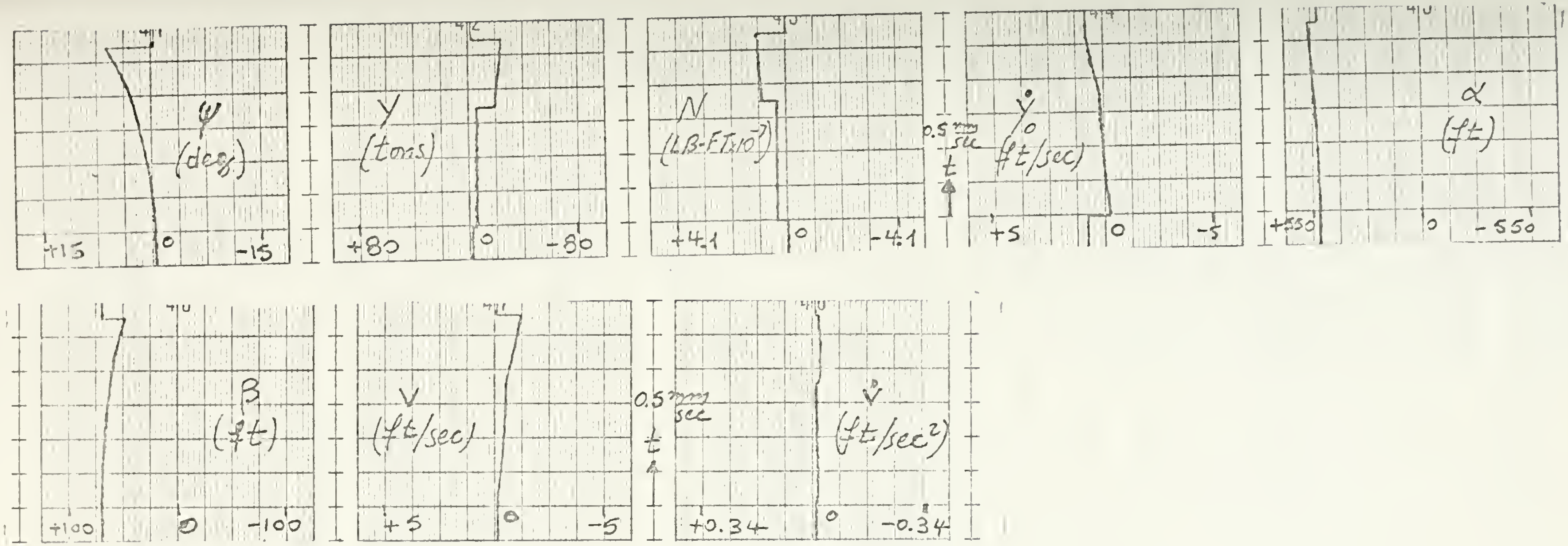


Figure 64. Linear response of the leading ship for Phase I. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+524$ft, $\beta=70$ft)

During the same cycle of computation the digital computer inverts the sign of longitudinal distance, α, and for the same lateral distance, β, gives another pair of Y-force and N-moment to the analog computer, which are the interaction effects applied to the tracking ship.

a. Stationary Runs (i.e. both ships have same propeller speed)

Figures 65 to 75 show the linear response of both the leading ship and the tracking ship alongside at the same speed of 15 knots at various longitudinal and lateral distances respectively. The responses were calculated in terms of the perturbated parameters $\psi_A, Y_A, N_A, \dot{y}_A$, α, β, $\dot{y}_{o_B}$, ψ_B where the indices A and B mean the leading ship (ship A) and tracking ship (ship B) respectively. Depending upon the relative position of the ships there are cases of attraction between them and repulsion between them. An interesting case was observed at the exactly abeam position, while the two ships were alongside at 70 ft lateral separation distance. The lateral distance was kept constant at 70 ft throughout the time of recording although both ships were yawing at negative angles.

b. Runs with Different Propeller Speed between Ship A (Leading Ship) and Ship B (Tracking Ship)

The assumption made for Phase I that both ships can possess any desired initial positions with respect to the (x_o, y_o) axes is carried throughout phase II, since again the tracking ship was never able to completely overtake the leading ship during the progress of a single run.

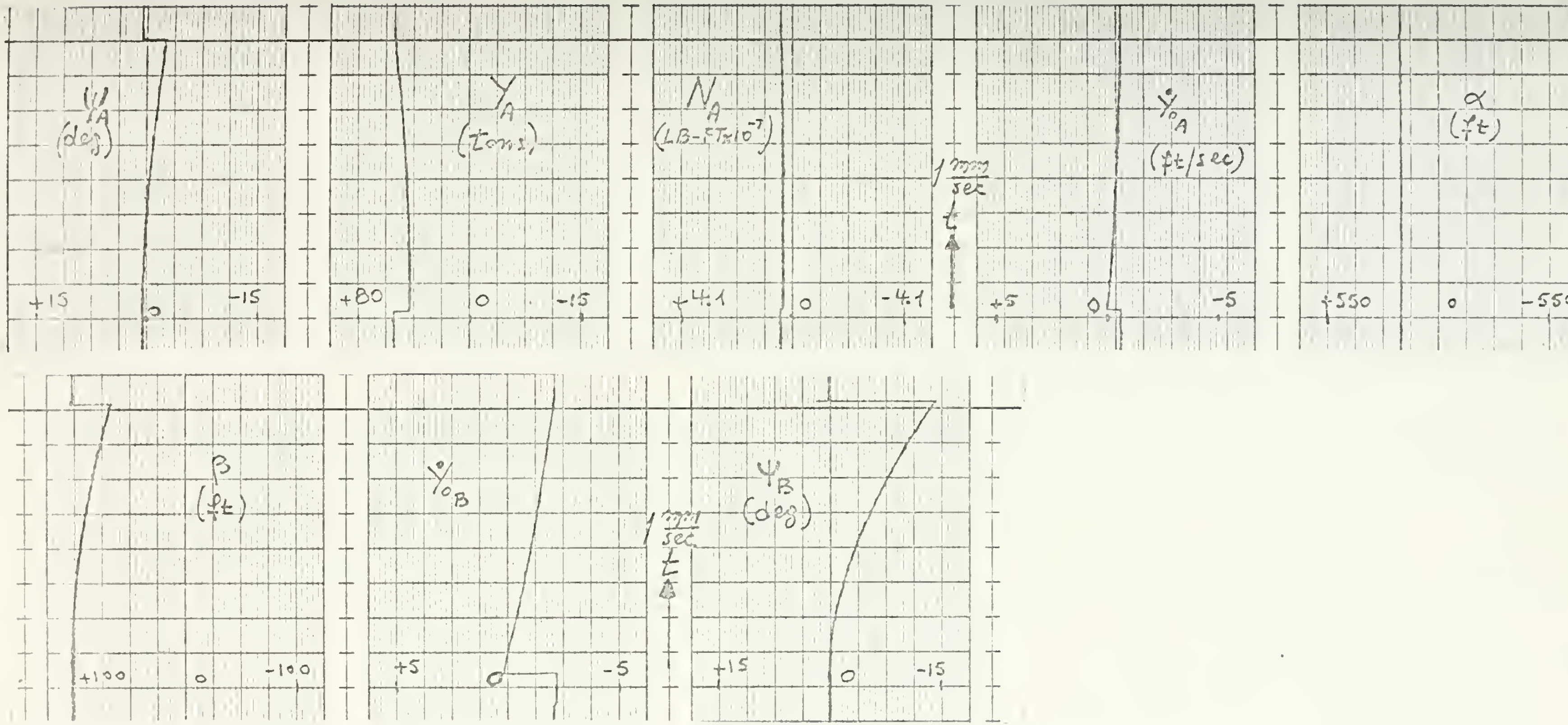


Figure 65. Linear response to ineraction effects for Phase II.
($\Delta R=0$, $\delta n=0$, $\alpha=+160ft$, $\beta=70ft$)

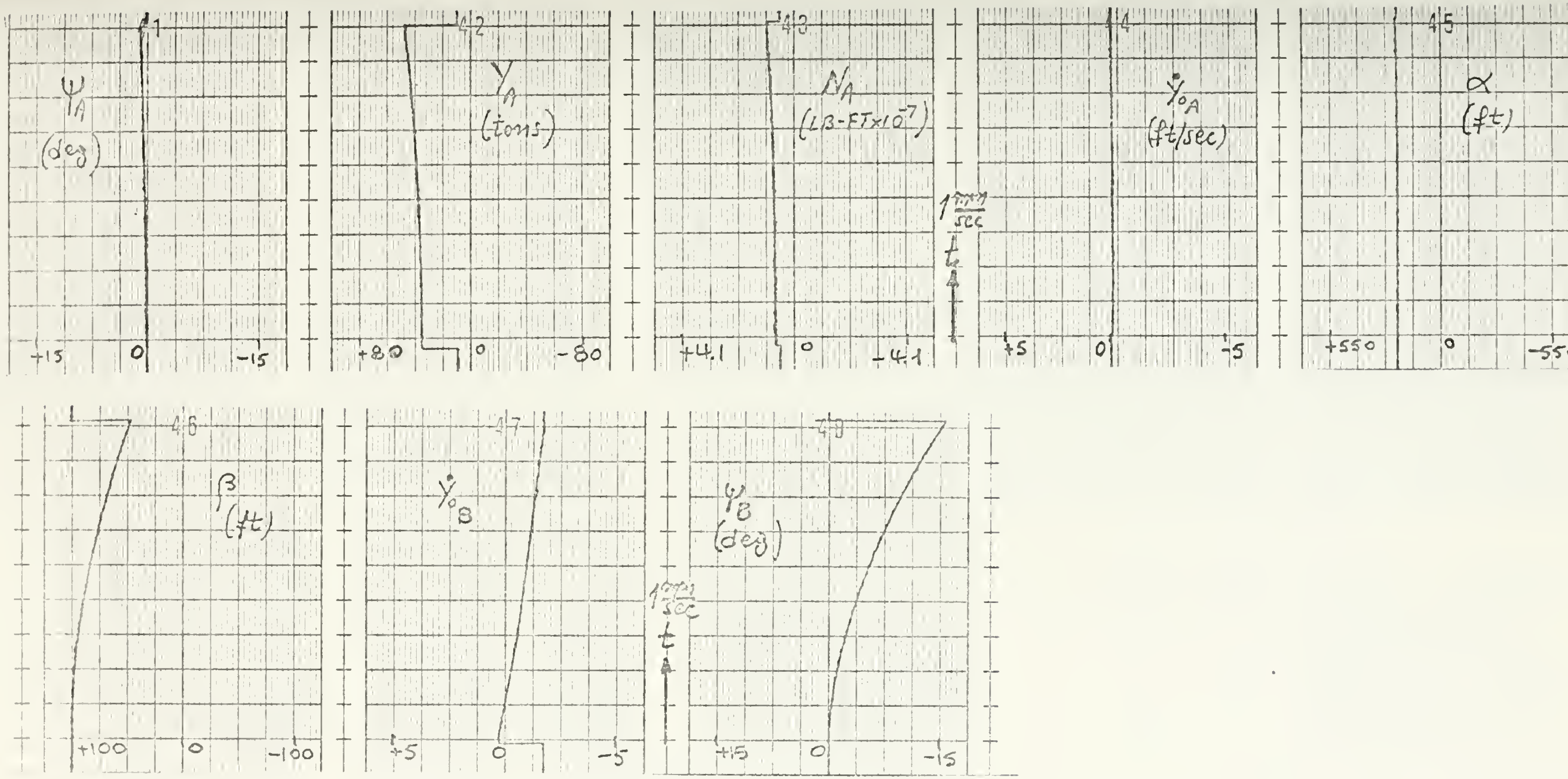


Figure 66. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=0$, $\alpha=+200ft$, $\beta=100ft$)

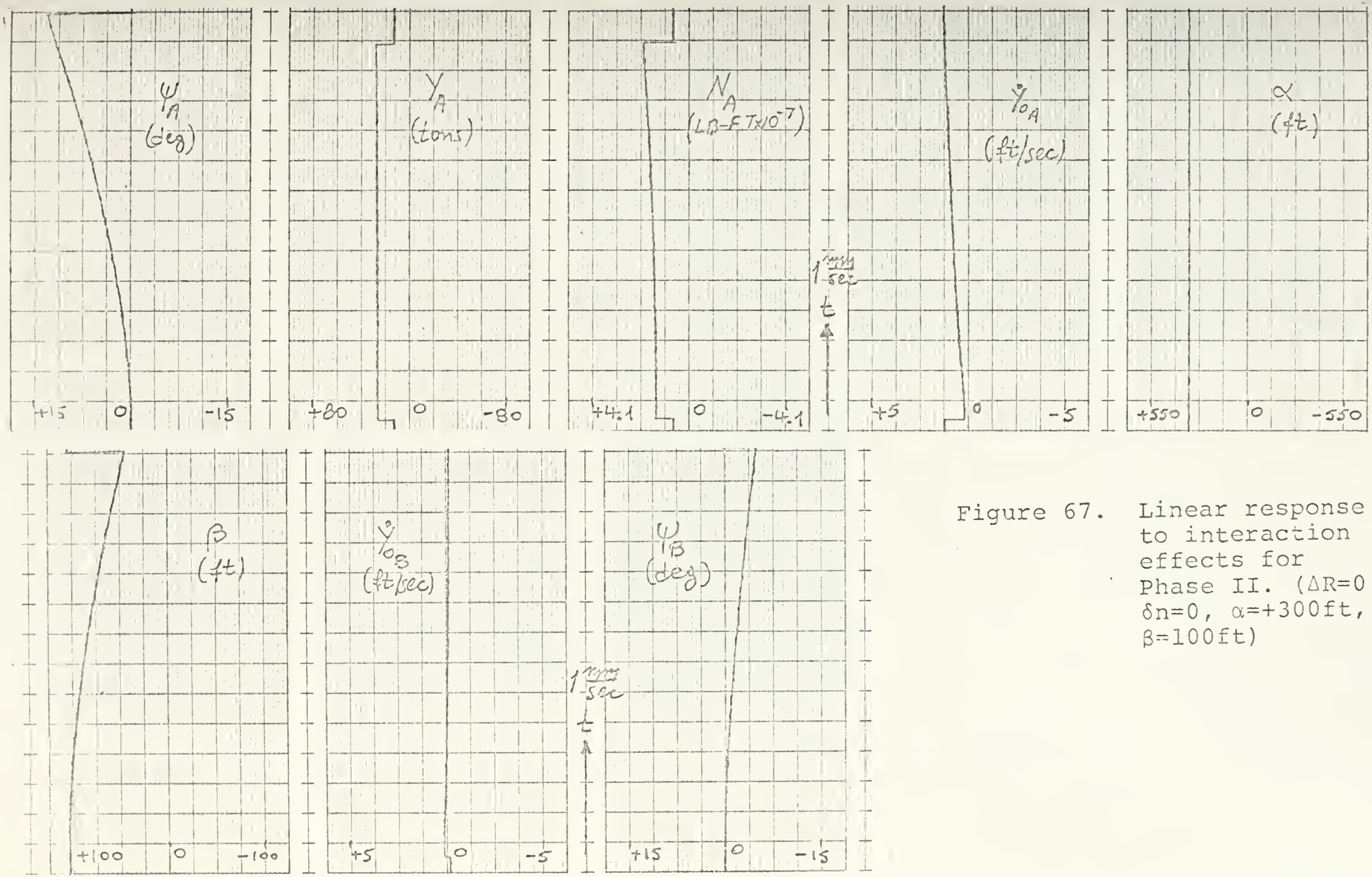


Figure 67. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=0$, $\alpha=+300$ft, $\beta=100$ft)

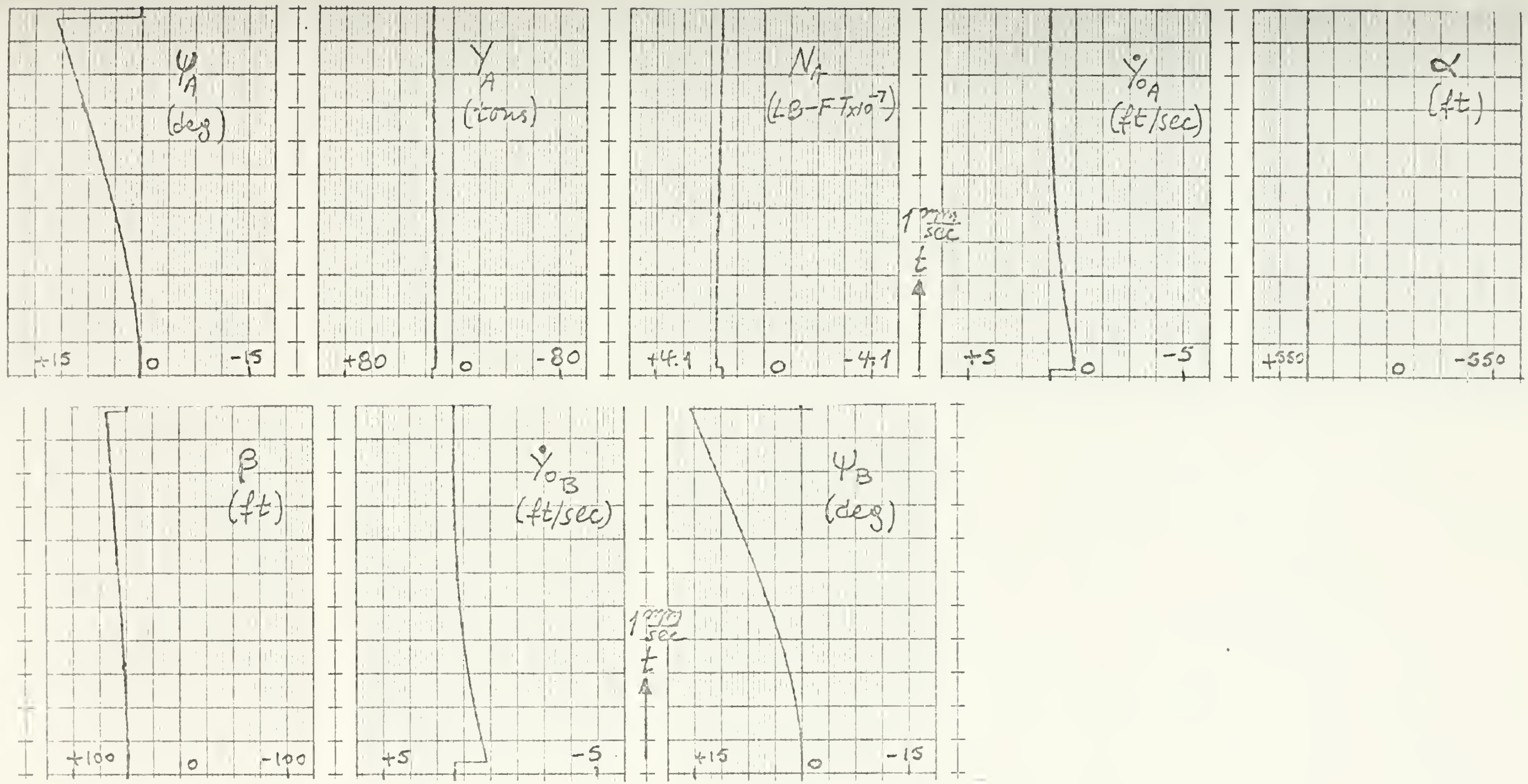


Figure 68. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=0$, $\alpha=+400$ft, $\beta=50$ft)

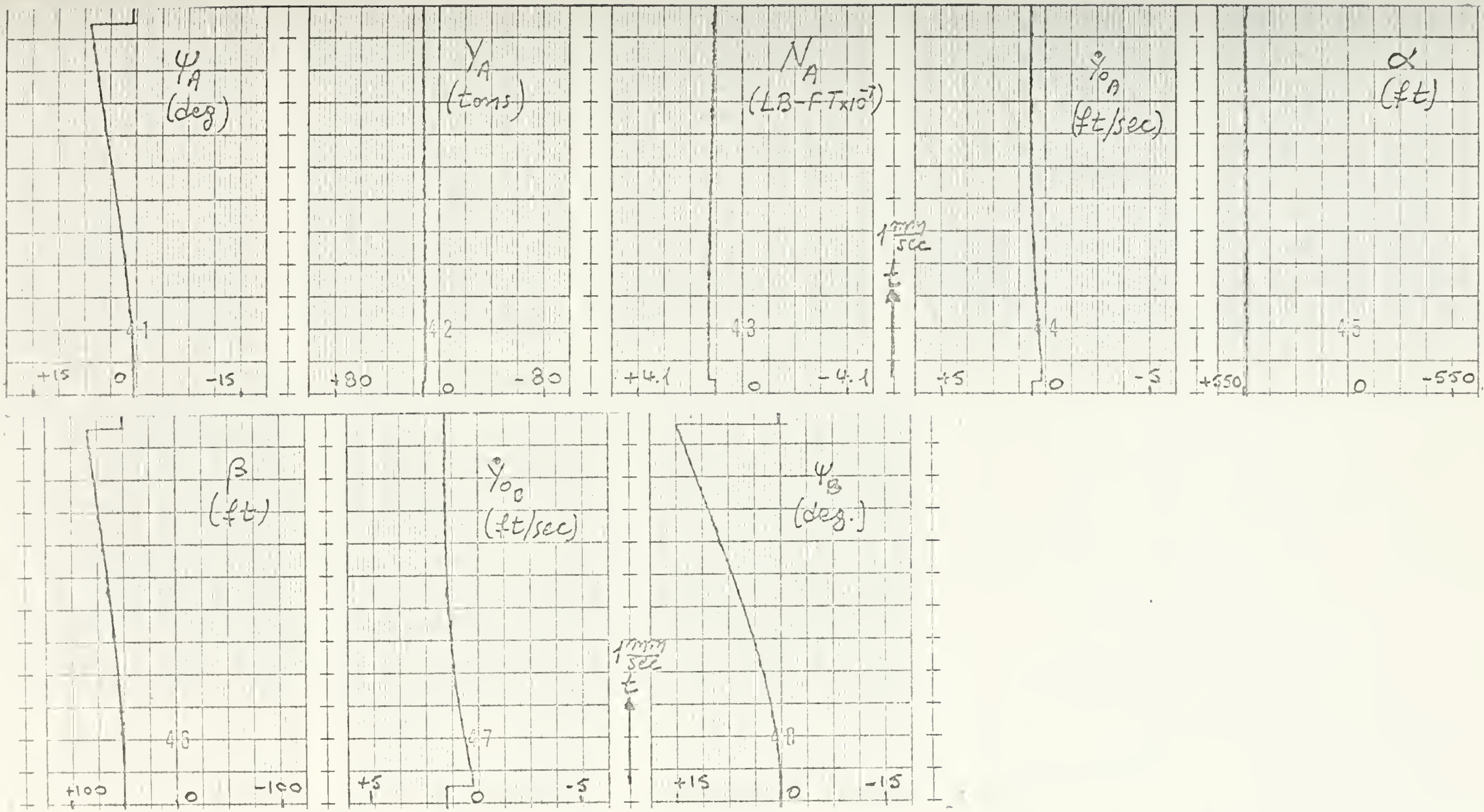


Figure 69. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=0$, $\alpha=+524ft$, $\beta=50ft$)

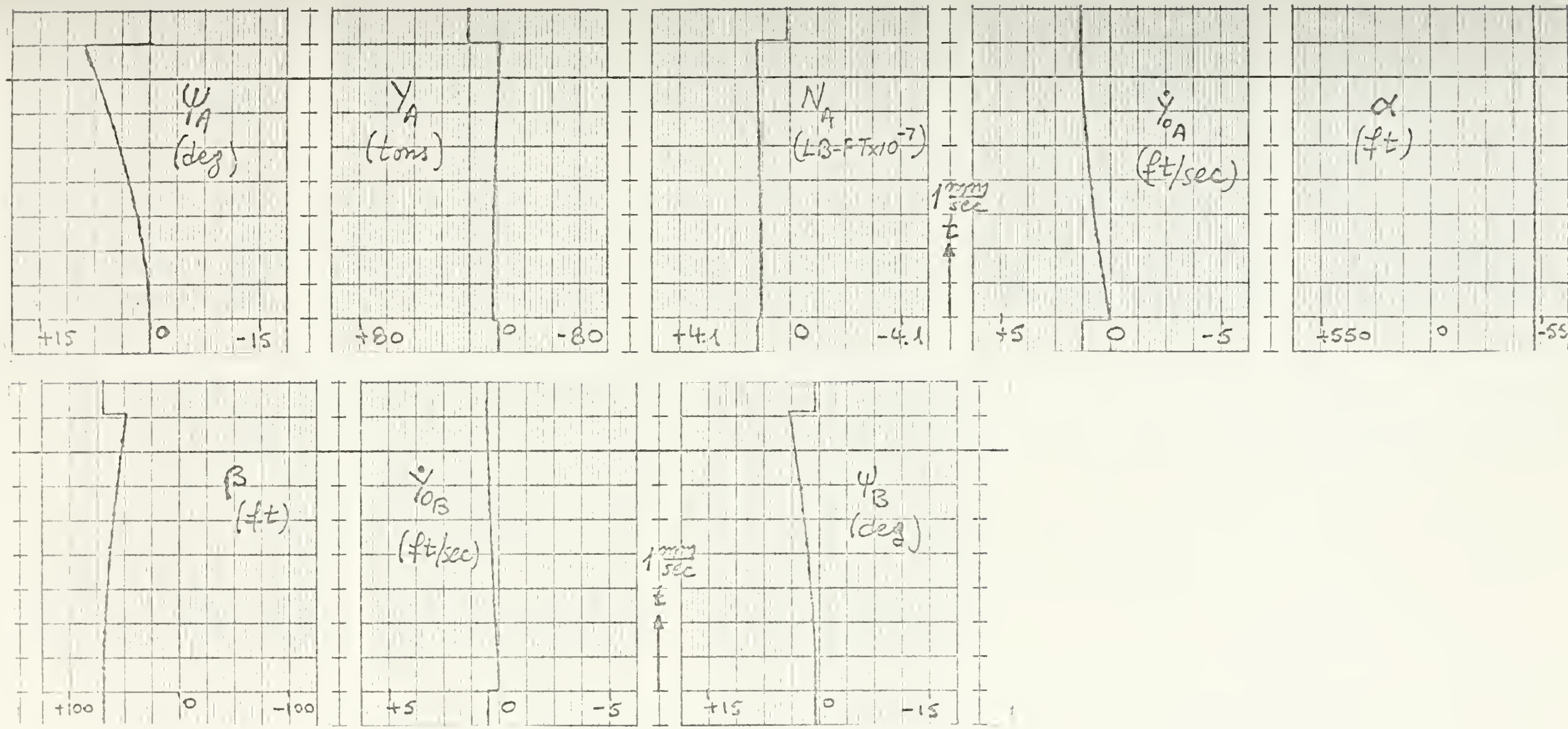


Figure 70. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=0$, $\alpha=-524$ft, $\beta=70$ft)

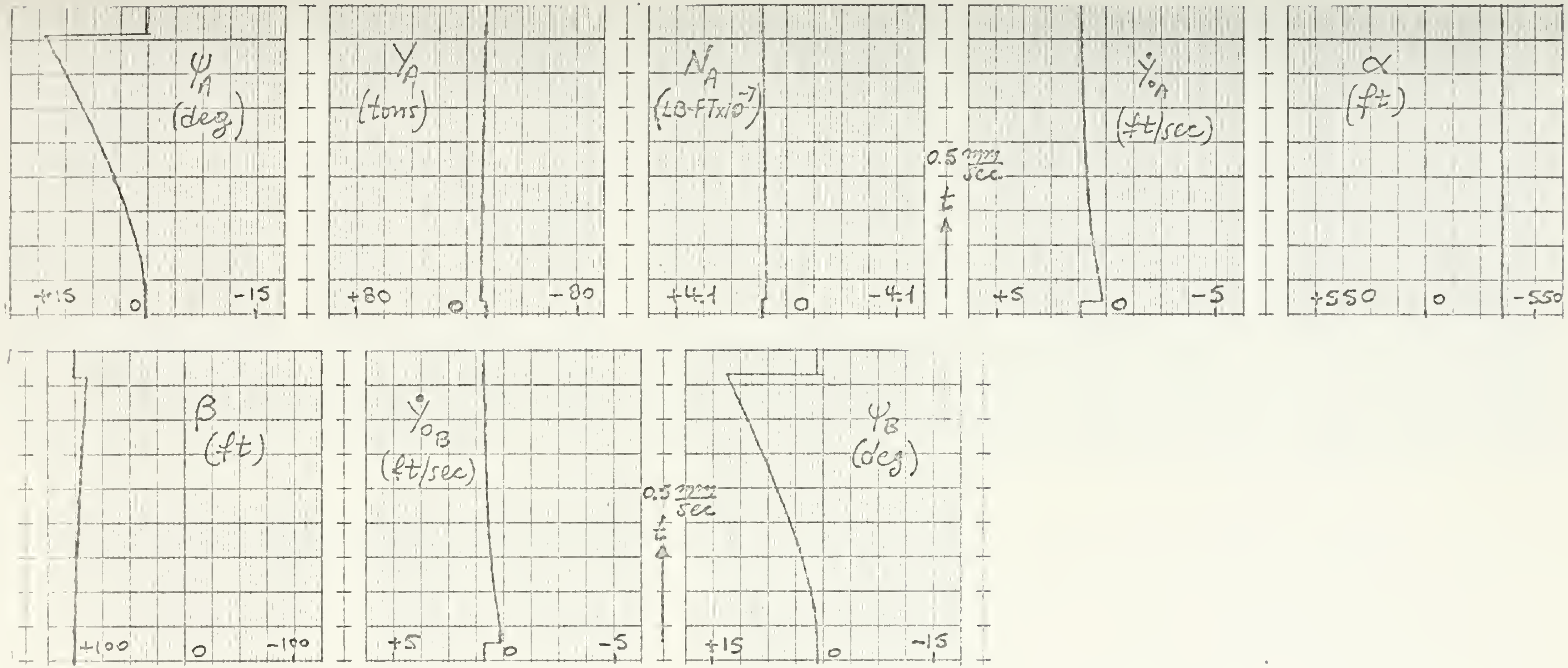


Figure 71. Linear response to interaction effects for Phase II.
(ΔR=0, δn=0, α=−400ft, β=100ft)

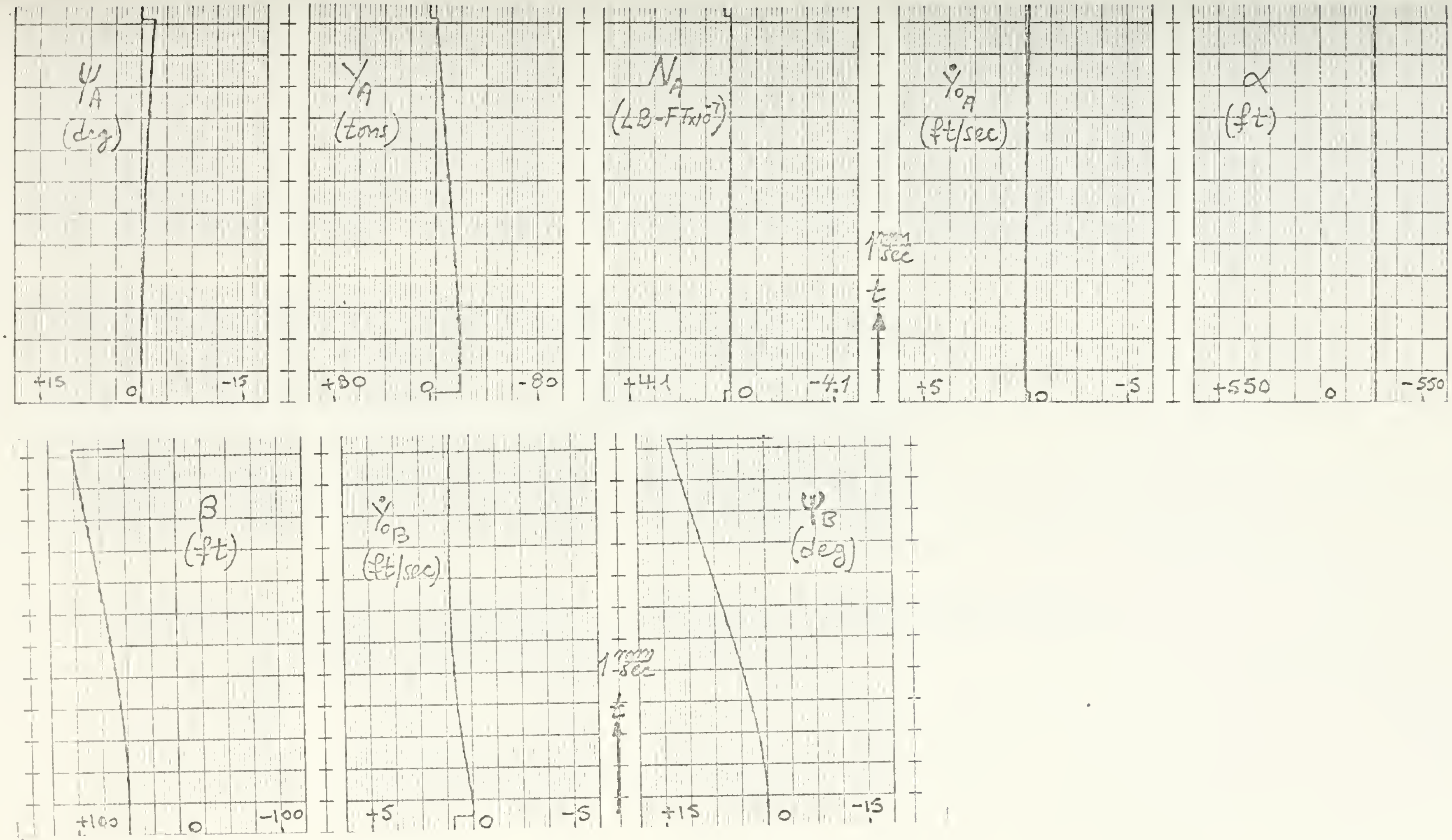


Figure 72. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=0$, $\alpha=-300ft$, $\beta=50ft$)

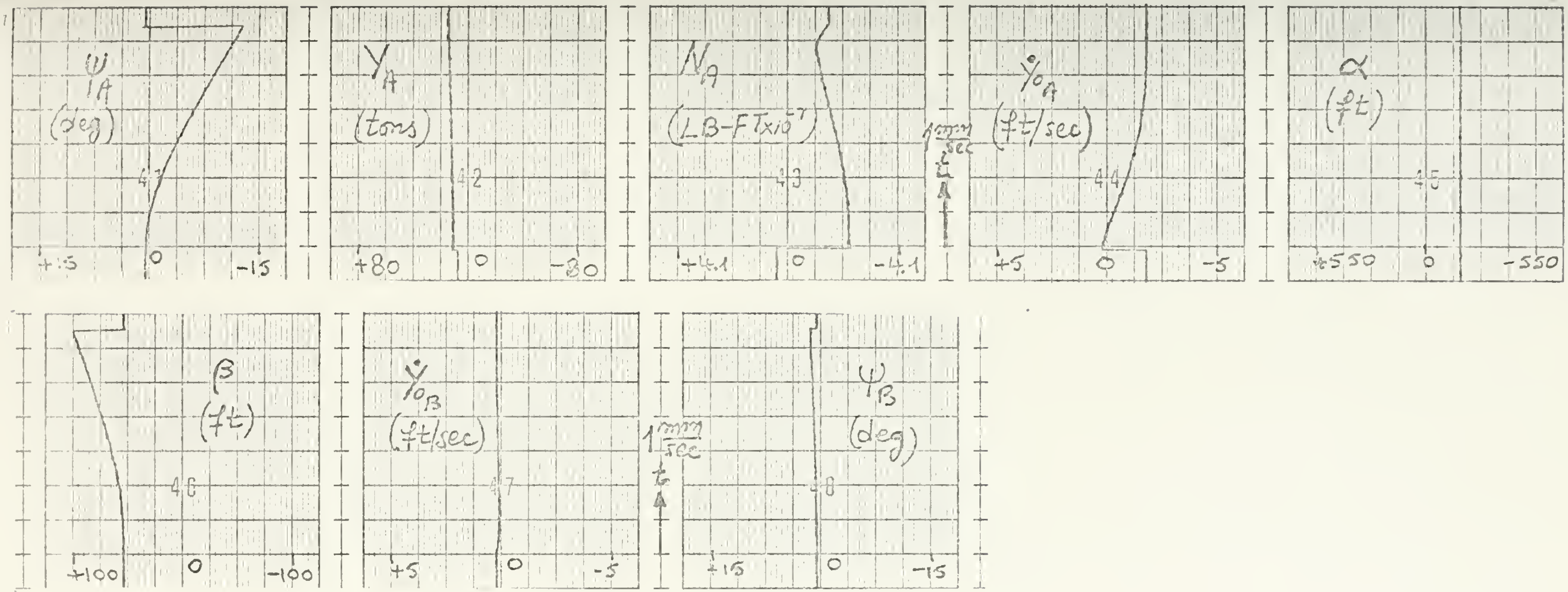


Figure 73. Linear response to interaction effects for Phase II.
(ΔR=0, δn=0, α=−200ft, β=50ft)

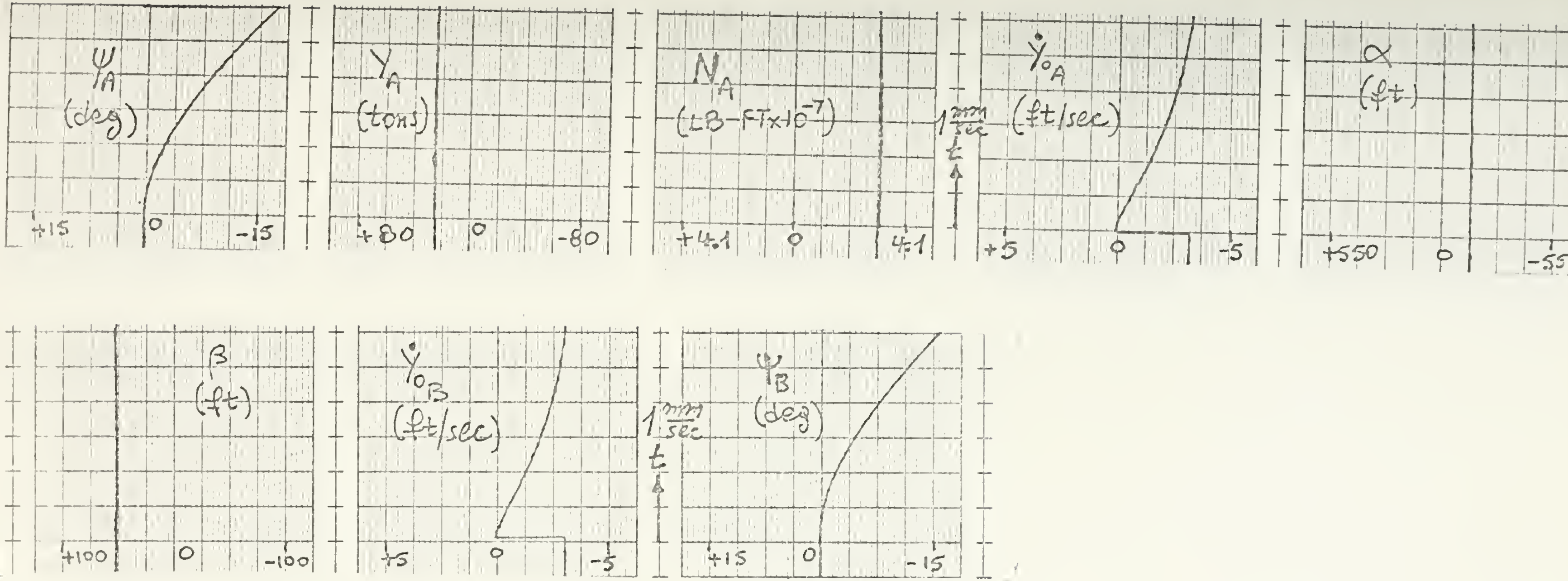


Figure 74. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=0$, $\alpha=-160$ft, $\beta=50$ft)

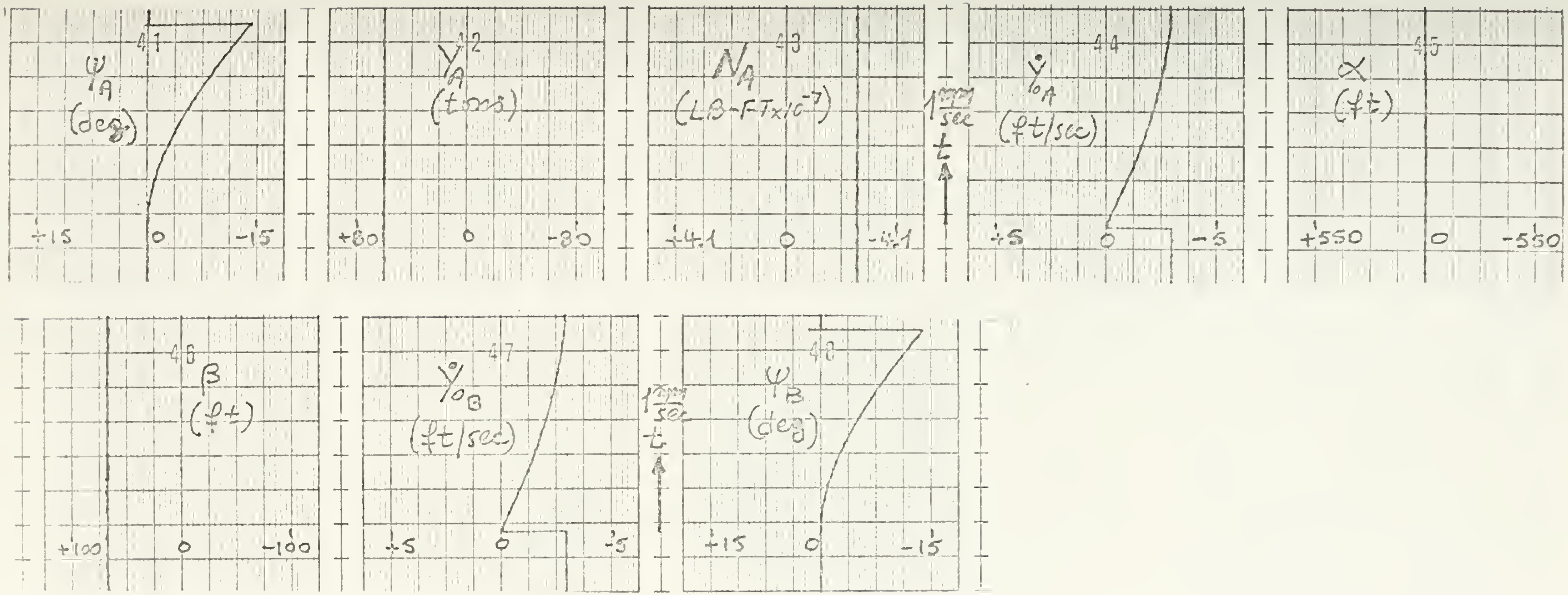


Figure 75. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=0$, $\alpha=0$, $\beta=70ft$)

The obtained responses were calculated in terms of the perturbated parameters ψ_A, Y_A, N_A, $\dot{y}_{o_A}$, α, β, $\dot{y}_{o_B}$, ψ_B where the indices A and B mean ship A and ship B respectively. With no controls applied on both ships the tracking ship was chosen to have in the first case 10 RPM propeller speed and in the second case 5 RPM propeller speed greater than the speed of 15 knots, which was the leading ship's speed.

In Figure 76 the initial position of the tracking ship is at (−524 ft, 70 ft) and that of the leading ship at (0,0). Obviously the longitudinal distance decreases since the tracking ship has a greater speed. The lateral distance, decreases also since the $\dot{y}_{o_A}$ velocity of the leading ship is positive and greater than the $\dot{y}_{o_B}$ velocity of the tracking ship, which is also positive. This means that the leading ship is pulled towards the tracking ship. It is seen also that the leading ship yaws to positive angles as well as the tracking ship but since the leading ship's yaw angles are greater than those of the tracking ship the stern of the leading ship comes towards the bow of the tracking ship.

Next in Figure 77 initially the longitudinal distance, α, and the lateral distance, β, were −400 ft and 70 ft respectively. The lateral distance, β, was decreasing until the longitudinal distance became roughly −250 ft. At this point both the interaction force and moment on the

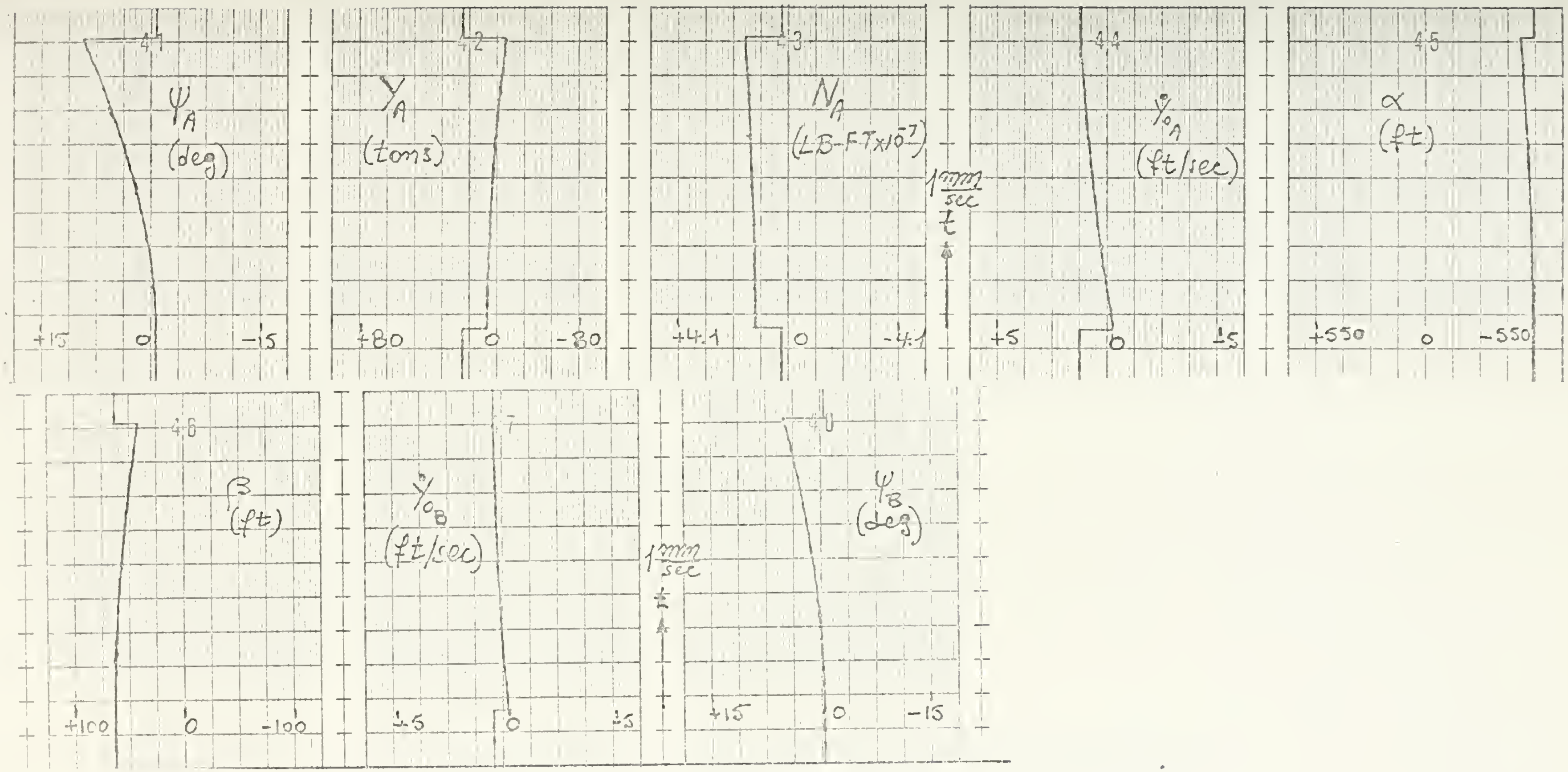


Figure 76. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=-524$ft, $\beta=70$ft)

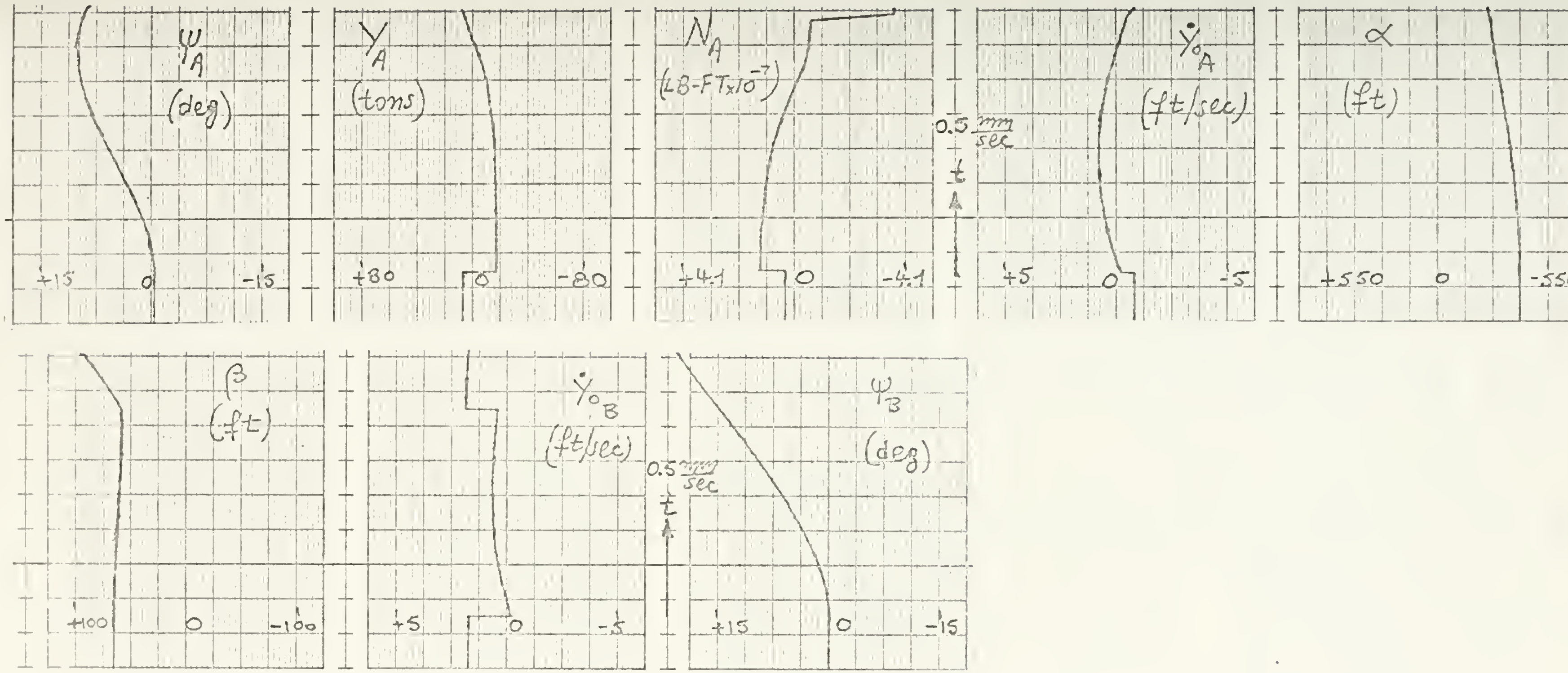


Figure 77. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=-400$ft, $\beta=70$ft)

leading ship changed sign. This can be observed in Figure 78 where initially α and β were −300 ft and 50 ft respectively. The above mentioned change of sign results in a negative leading ship's yaw angle, while the tracking ship continues to have positive yaw angle. The lateral distance starts to increase from the instant at which the longitudinal distance is roughly −250 ft.

In Figure 79 α and β were initially −200 ft and 50 ft respectively. It can be seen that the leading ship yaws to negative yaw angles while the tracking ship maintains zero yaw angle. Although this is happening the $\dot{y}_{O_A}$ velocity is negative and the $\dot{y}_{O_B}$ almost zero. Hence the leading ship is pushed away from the tracking ship and the lateral distance is increased.

The same analysis can be done for the response of Figure 80a where α and β were initially −160 ft and 70 ft respectively as well as for the response of Figure 80b where initially was set $\alpha = -160$ ft and $\beta = 50$ ft.

Figure 81 shows the response obtained for the exactly abeam position of the two ships being alongside. It is seen although both ships are yawing excessively to negative angles the lateral distance is slightly increasing. Hence this is the best position for station keeping.

Figure 82 shows the obtained response for α and β being initially +160 ft and 100 ft respectively. It is seen that the lateral distance β starts to decrease

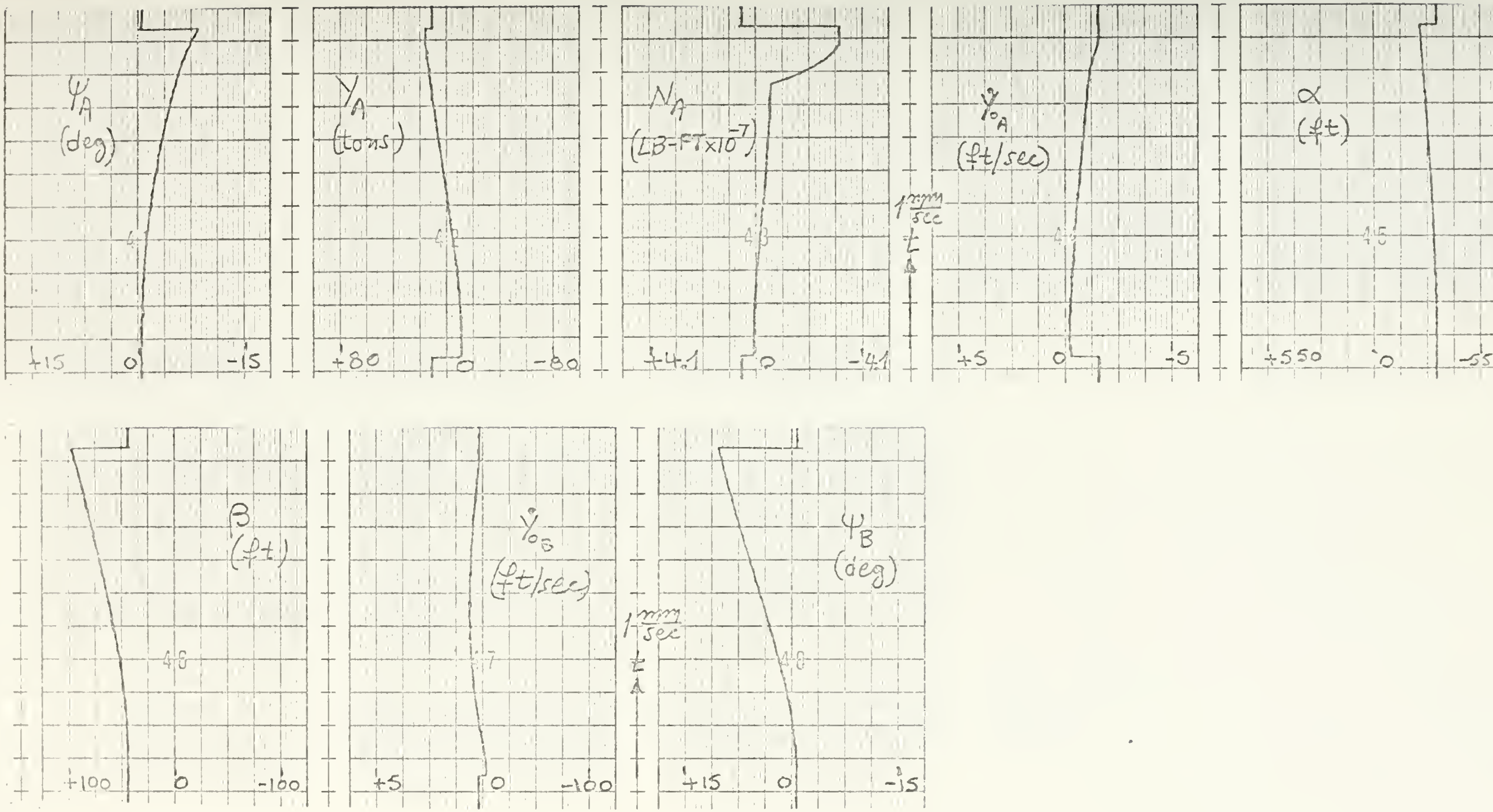


Figure 78. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=-300$ft, $\beta=50$ft)

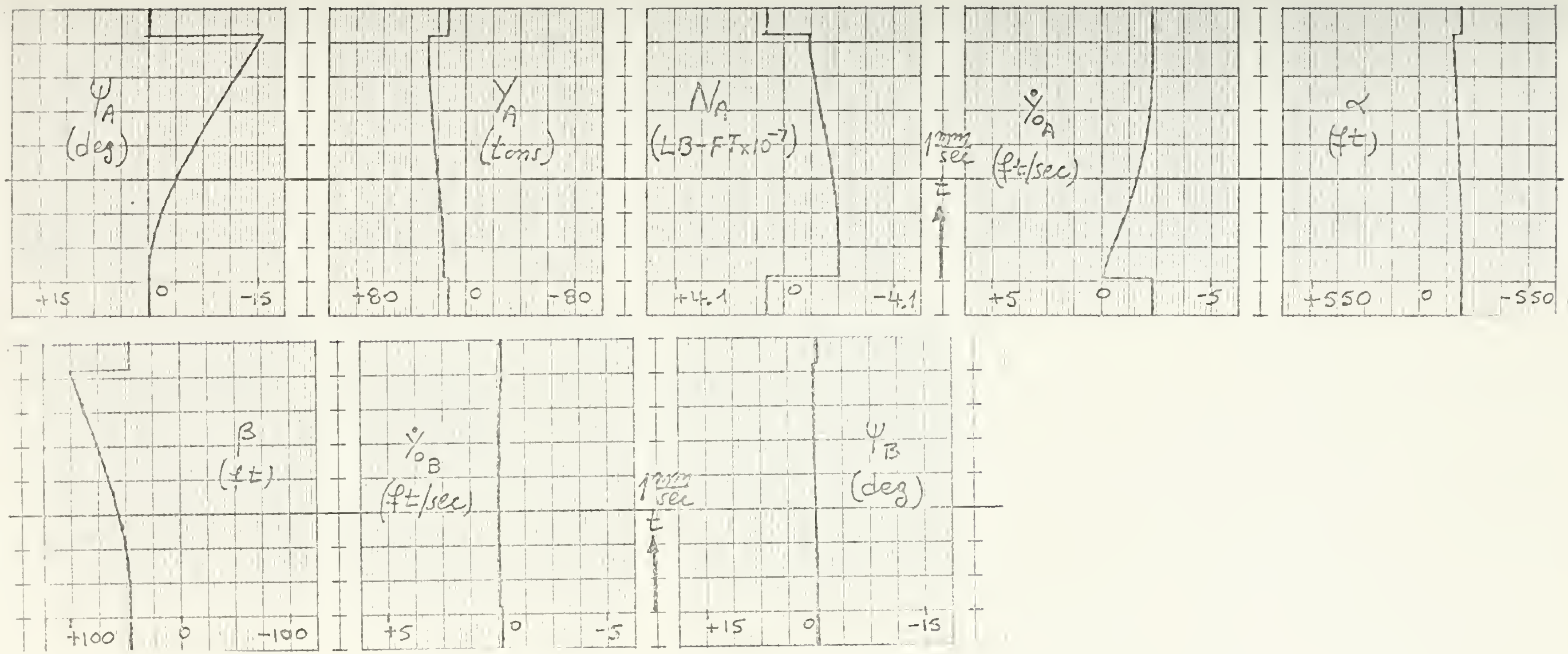


Figure 79. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=-200$ft, $\beta=50$ft)

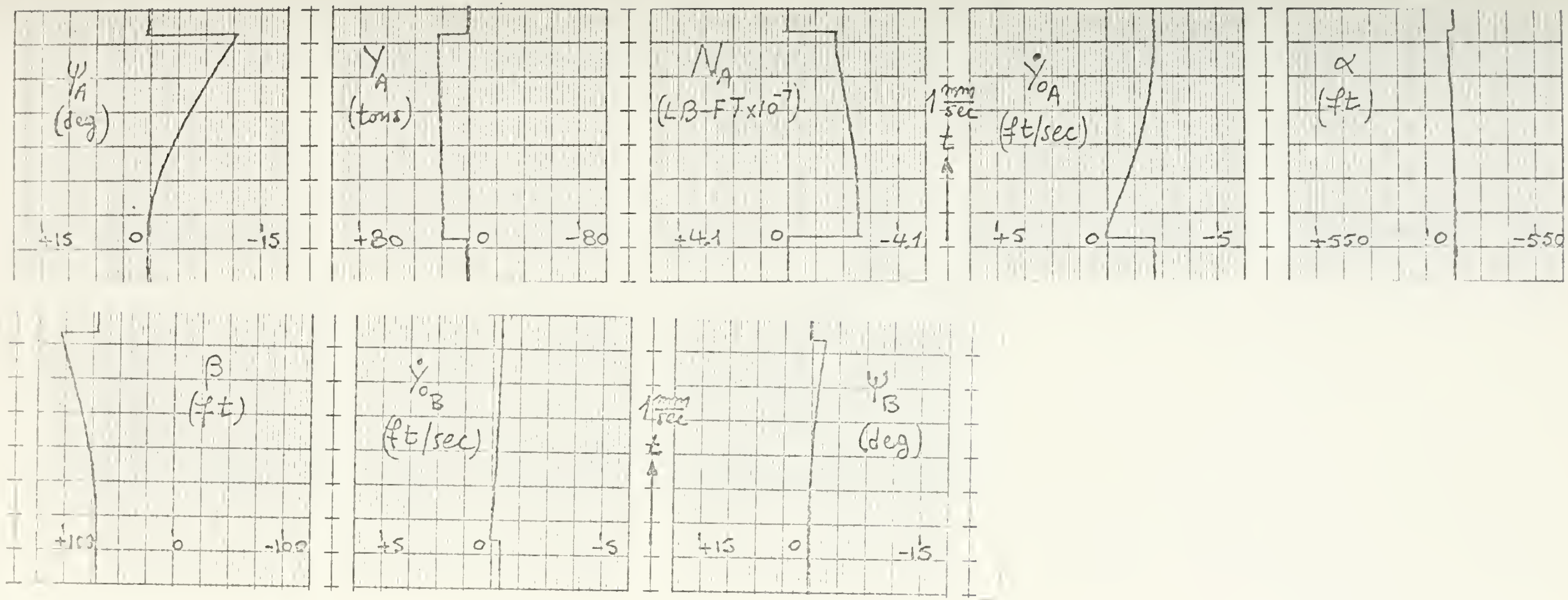


Figure 80a. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=-160$ft, $\beta=70$ft)

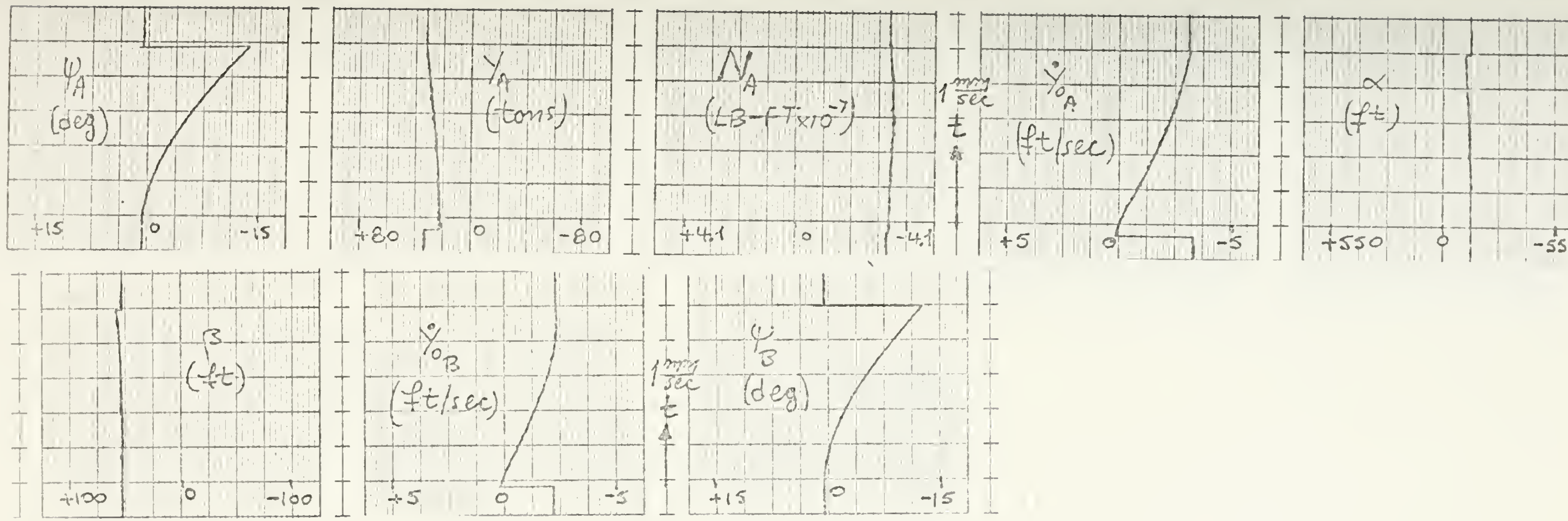


Figure 80b. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=-10$ RPM, initially $\alpha=-160$ft, $\beta=50$ft)

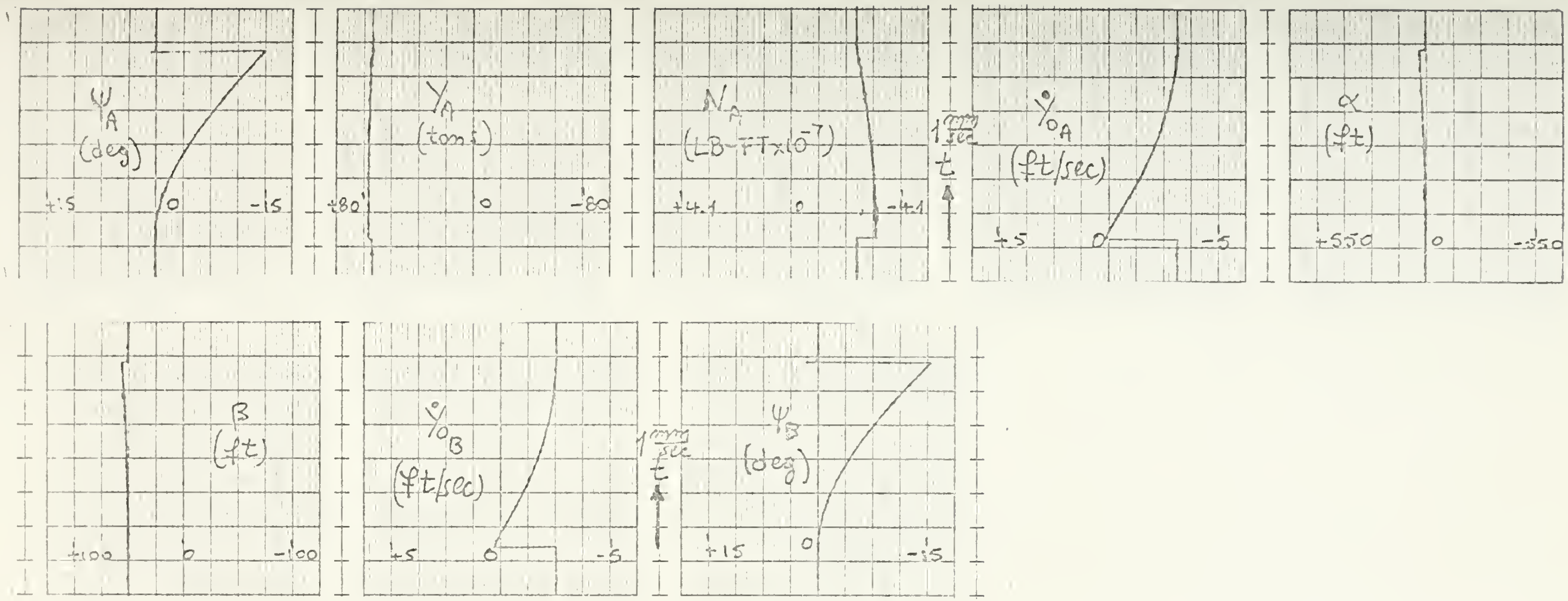


Figure 81. Linear response to interaction effects for Phase II. (ΔR=0, δn=+10 RPM, initially α=0, β=50ft)

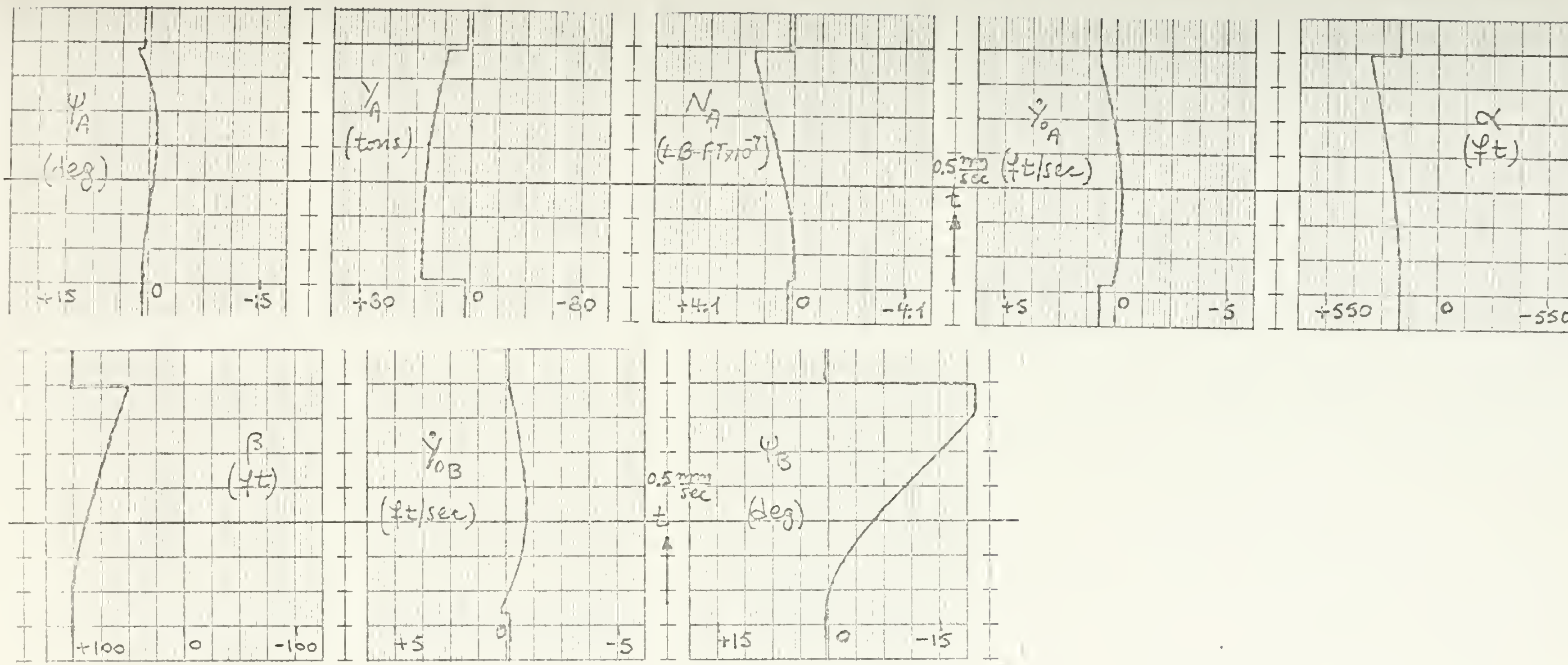


Figure 82. Linear response to interaction effects for Phase II.
(ΔR=0, δn=+10 RPM, initially α=+160ft,β=100ft)

when the longitudinal distance becomes roughly +200 ft, while the leading ship yaws slightly negatively and the tracking ship yaws excessively negatively. These facts bring the bow of the leading ship towards the tracking ship's stern. At +250 ft longitudinal separation between midships the leading ship reverses direction of yawing while the tracking ship continues to yaw negatively.

This can be seen more easily in the response of Figure 83 where initially α and β set at +200 ft and 100 ft respectively. Due to these opposite yaw angle directions the sterns of both ships are pulled toward each other while the lateral distance is decreasing. In Figure 84 α and β initially were set to be equal +300 ft and 70 ft respectively. The lateral distance is decreasing due to the fact that the leading ship's $\dot{y}_{o_A}$ velocity is positive and greater than that of the tracking ship. Also the leading ship yaws positively while the tracking ship yaws slightly negatively. This brings leading ship's stern towards the tracking ship. Note that at roughly +350 ft longitudinal separation the tracking ship reverses the direction of yawing. This tends to bring the bow of the tracking ship towards the stern of the leading ship.

Figures 85 and 86 show the responses for initially setting α and β +400 ft and +524 ft, 70 ft respectively. The lateral distance, β, is increasing although both ships yaw positively.

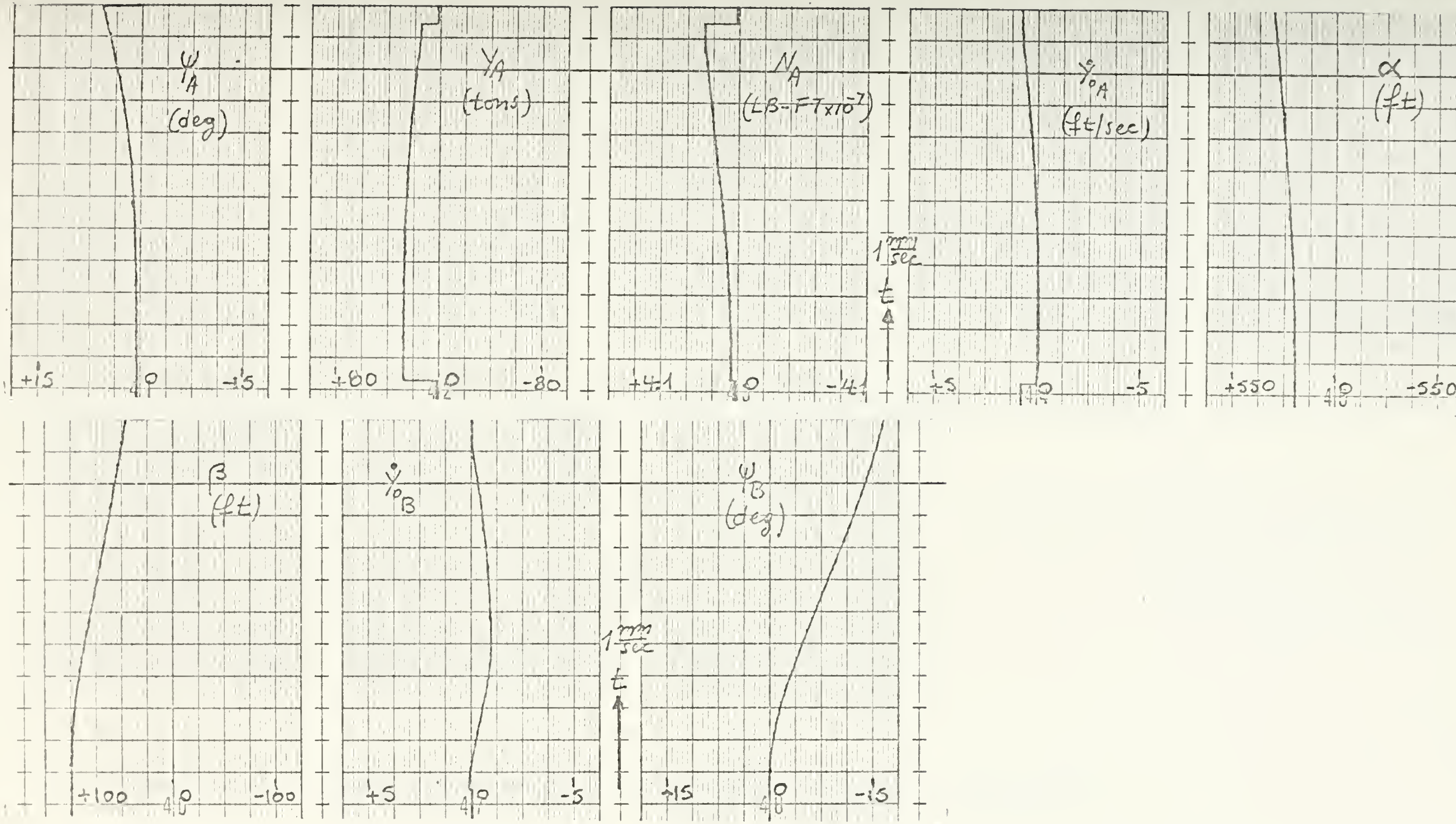


Figure 83. Linear response to interaction effects for Phase II.
(ΔR=0, δn=+10 RPM, initially α=+200ft, β=100ft)

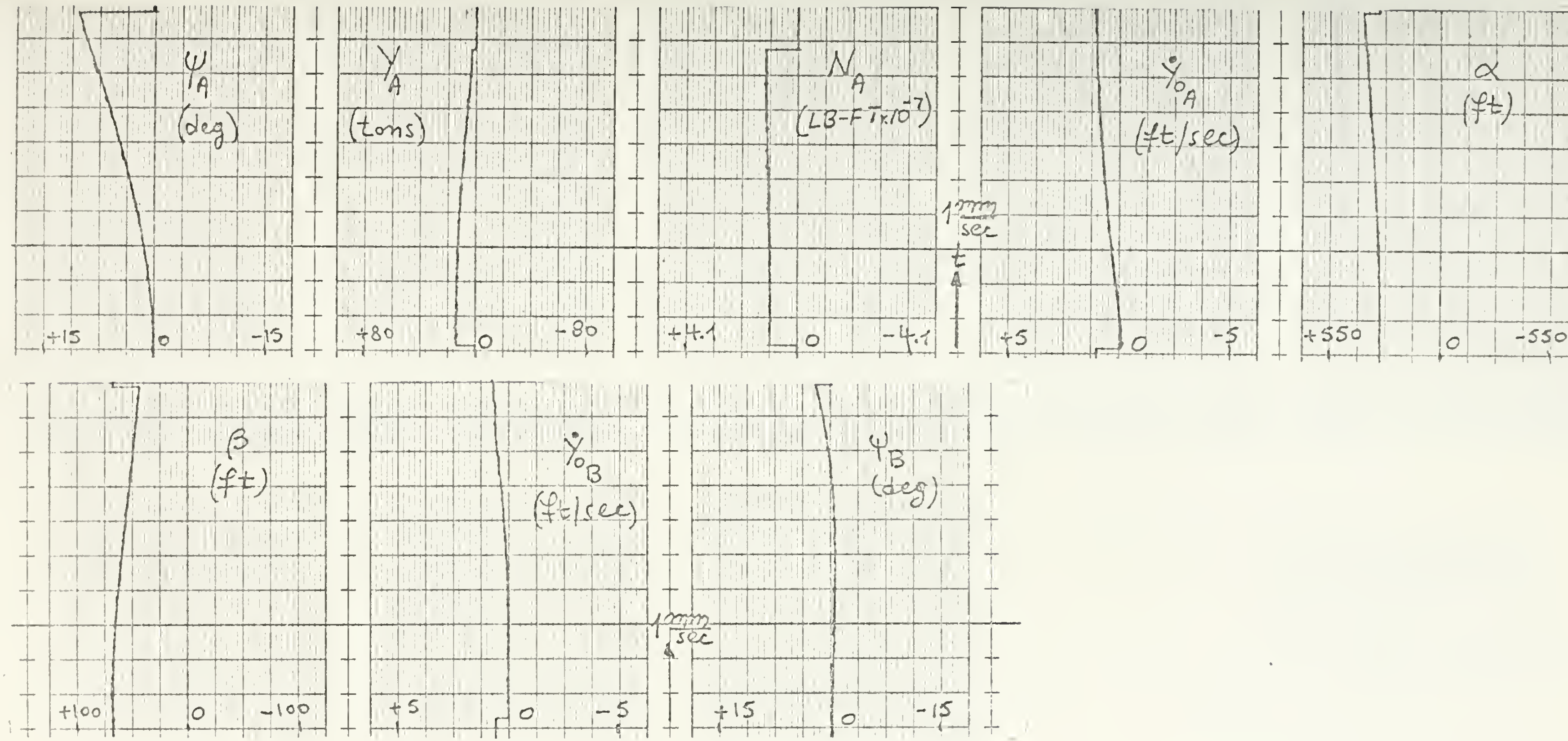


Figure 84. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=+300$ft, $\beta=70$ft)

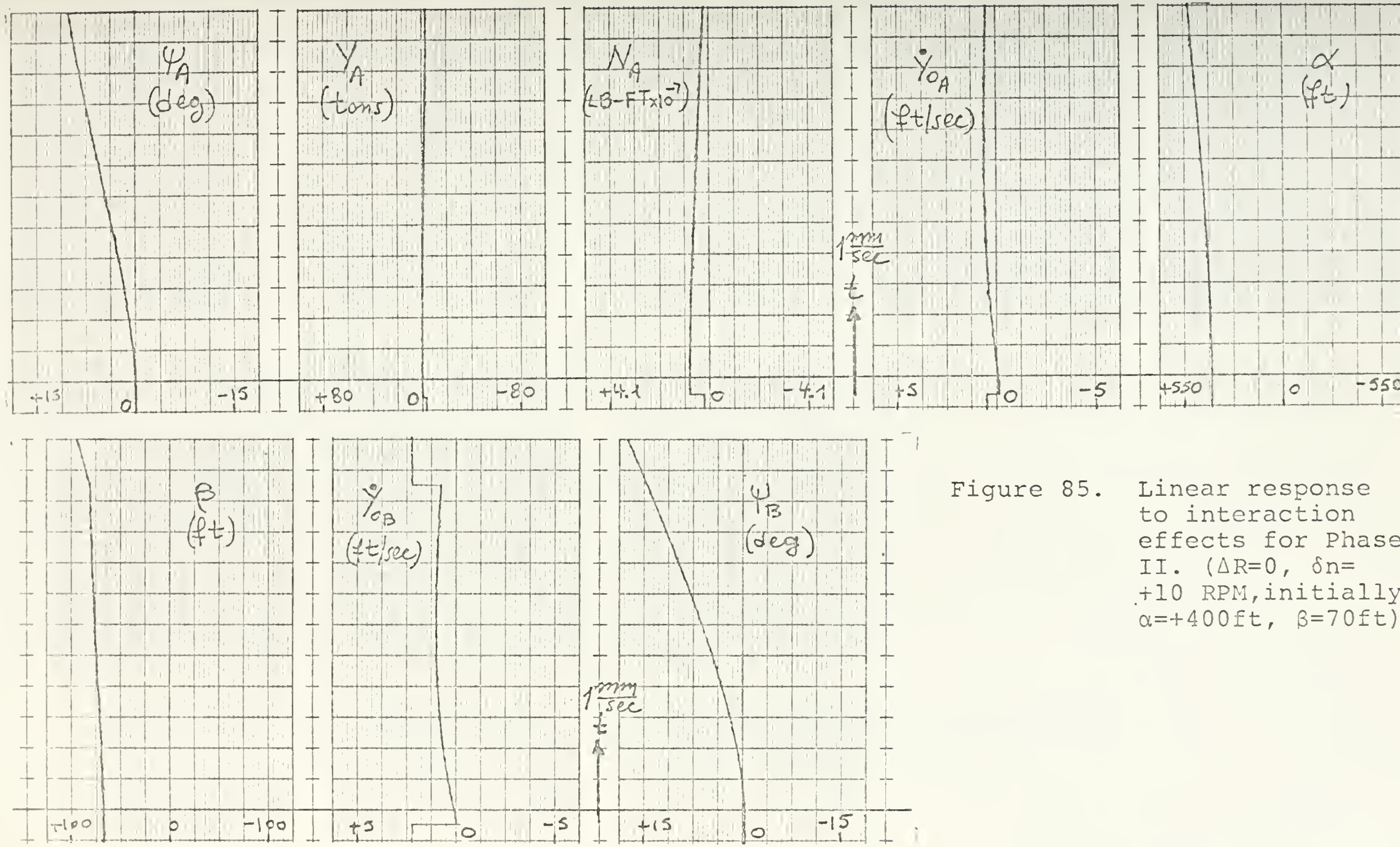


Figure 85. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=+400$ft, $\beta=70$ft)

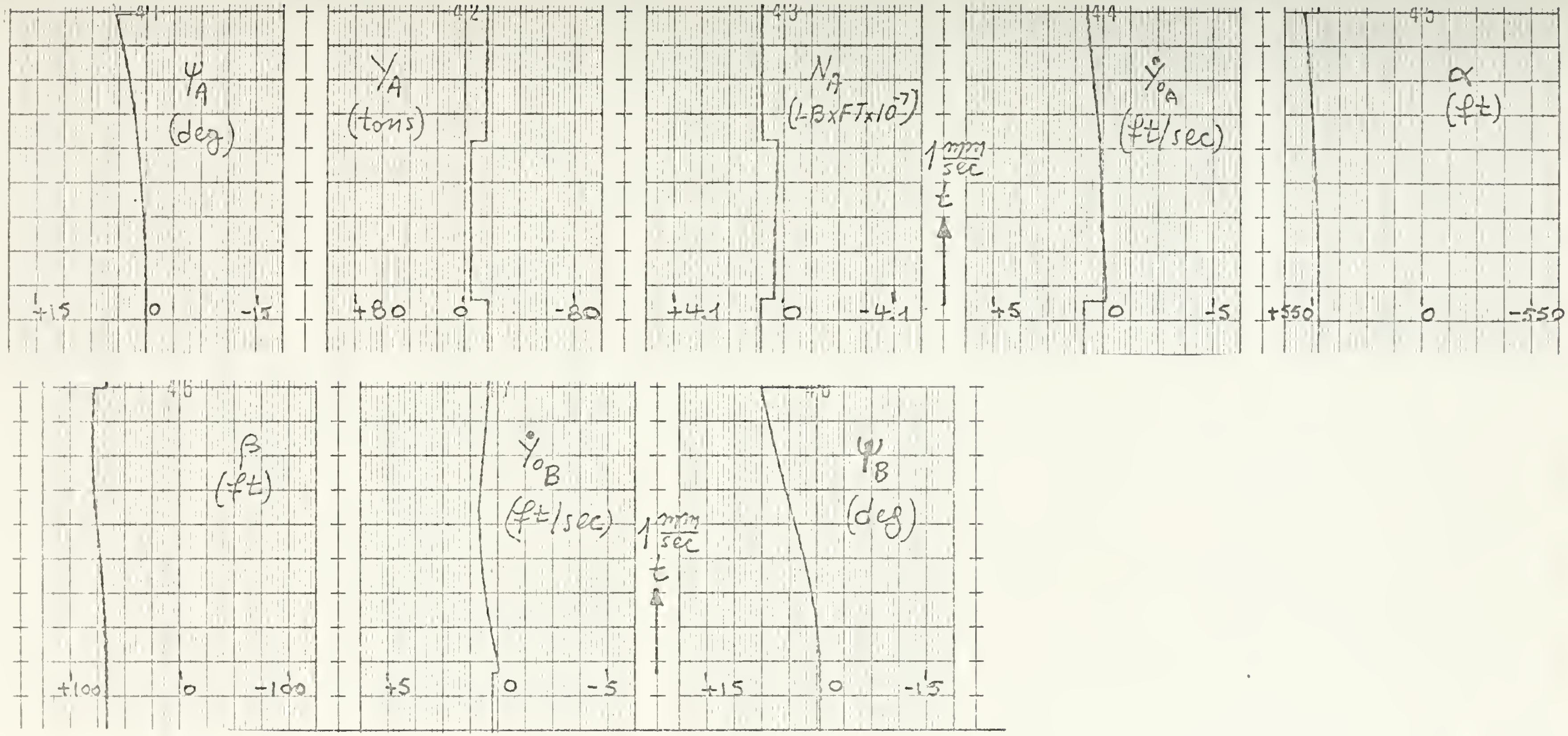


Figure 86. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+10$ RPM, initially $\alpha=+524$ft, $\beta=70$ft)

Figures 87 to 97 show the responses obtained for different initial positions of the ships. The analysis of these curves is analogous to the previous one, the difference being that the tracking ship has now a +5 RPM greater propeller speed than that of 15 knots. Note that for the smaller difference in propeller speed there is a smaller rate of change of the lateral separation distance although both ships yaw to greater values of yaw angles since they have adequate time for that.

c. Manual Control is Applied in Phase II

From the previous obtained responses it is obvious that control must be applied in order to keep a desired course as well as a lateral separation distance, β. Up till now for lateral distance greater than 100 feet or less than 50 feet the digital programming was made such that for these cases a zero force-Y and moment-N was given to the analog computer. This fact made impossible for the tracking ship to completely overtake the leading ship during only one run. At this point the following approximation was made to override this difficulty, namely the digital programming, Computer Program VII, was made such that the digital computer gives (for values of β outside the table limits) the values of Y-force and N-moment corresponding to the extreme values of β, i.e. 50 ft and 100 ft. Obviously in the actual case the interaction effects would be more pronounced for β less than 50 ft and less pronounced for β greater than 100 ft. But with this

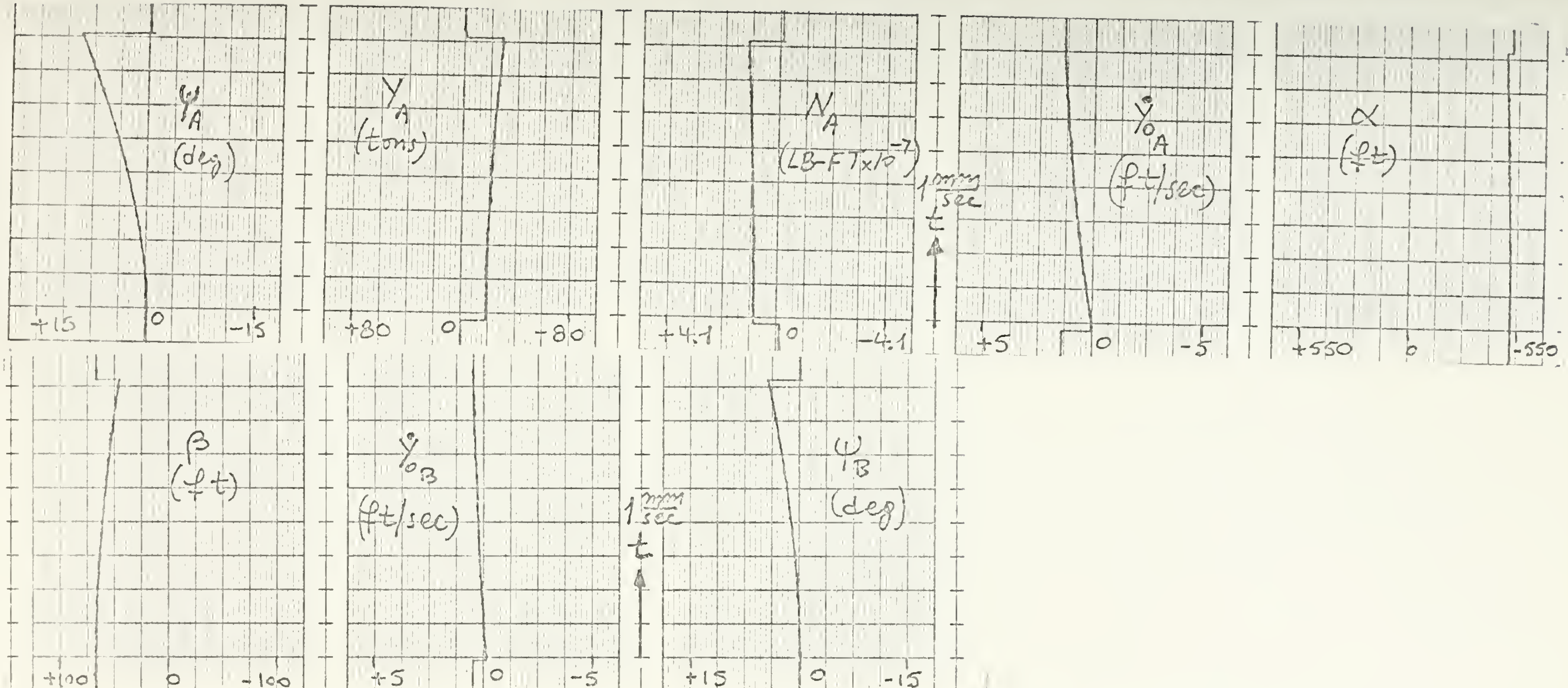


Figure 87. Linear response to interaction effects for Phase II.
(ΔR=0, δn=+5 RPM, initially α=−524ft, β=70ft)

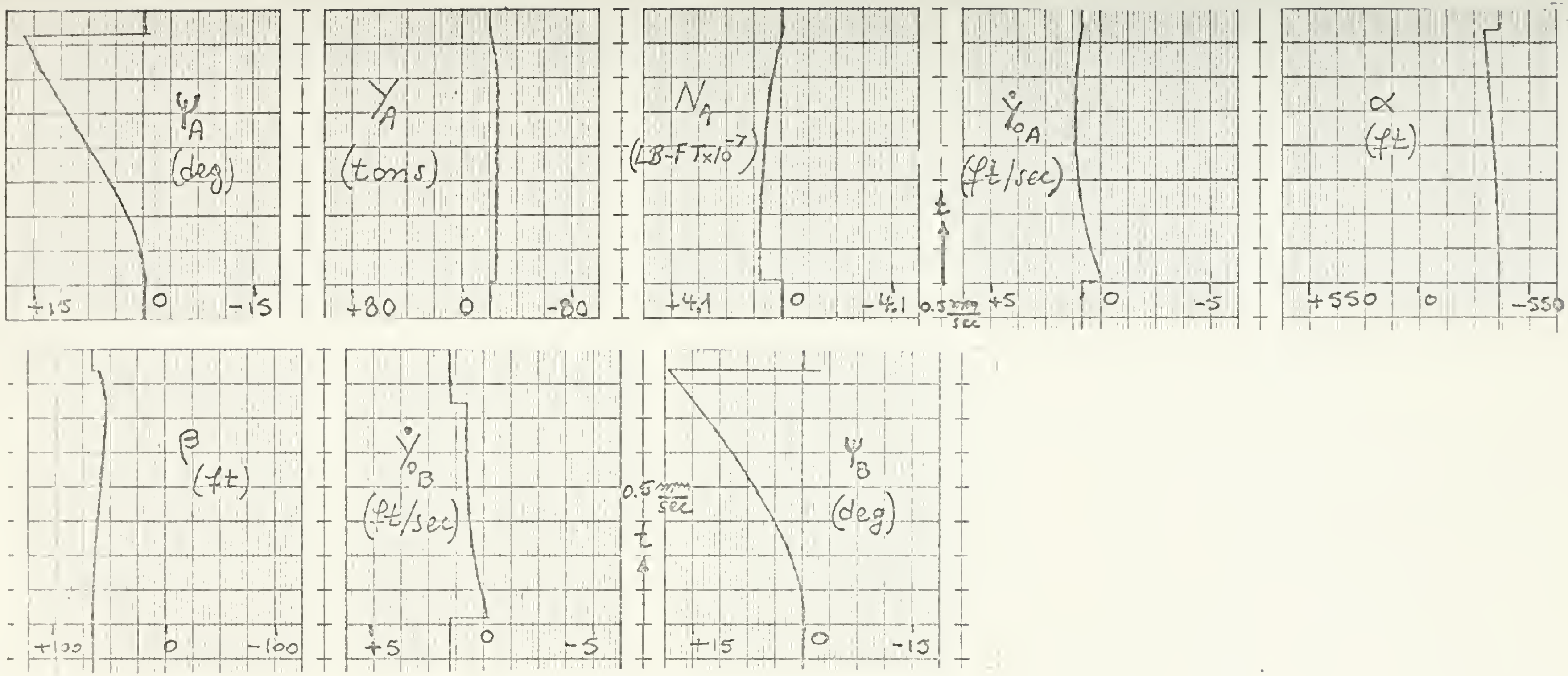


Figure 88. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+5RPM$, initially $\alpha=-400ft$, $\beta=70ft$)

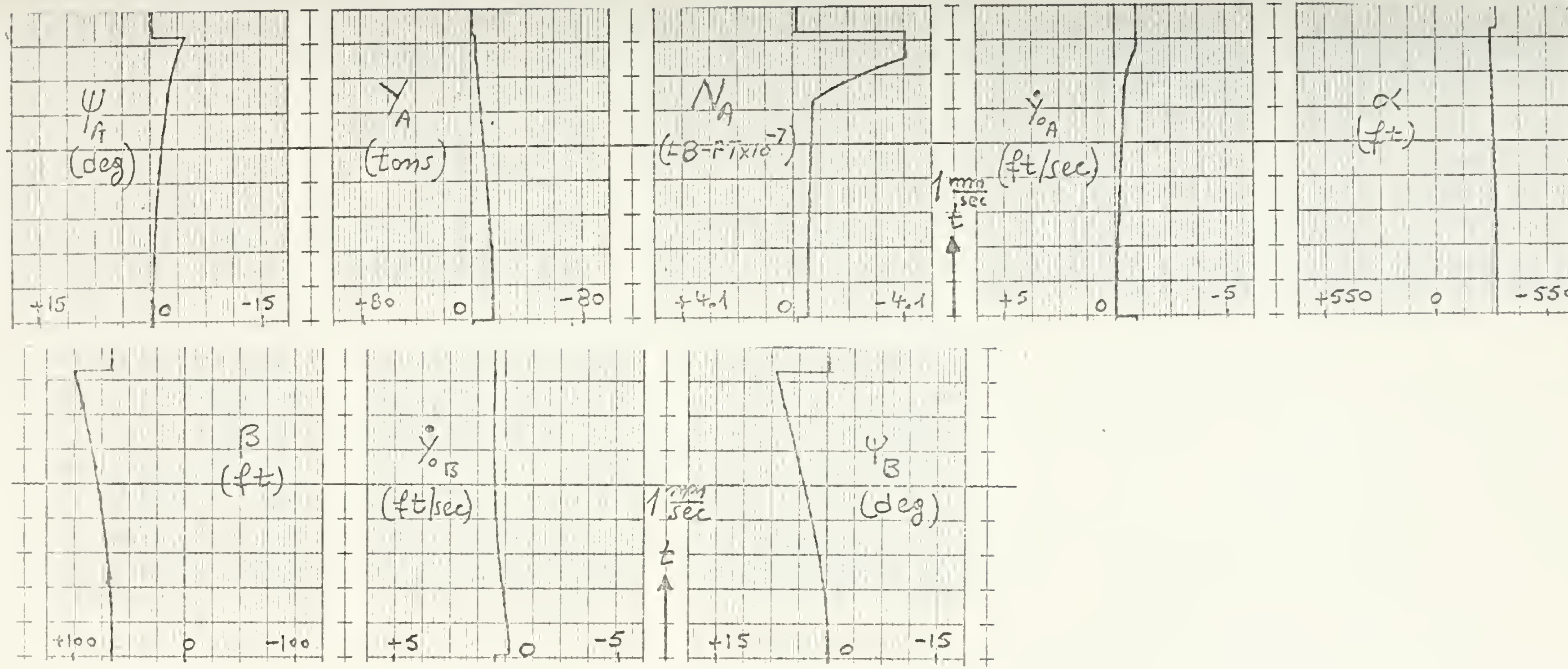


Figure 89. Linear response to interaction effects for Phase II.
(ΔR=0, δn=+5 RPM, initially α=−300ft, β=70ft)

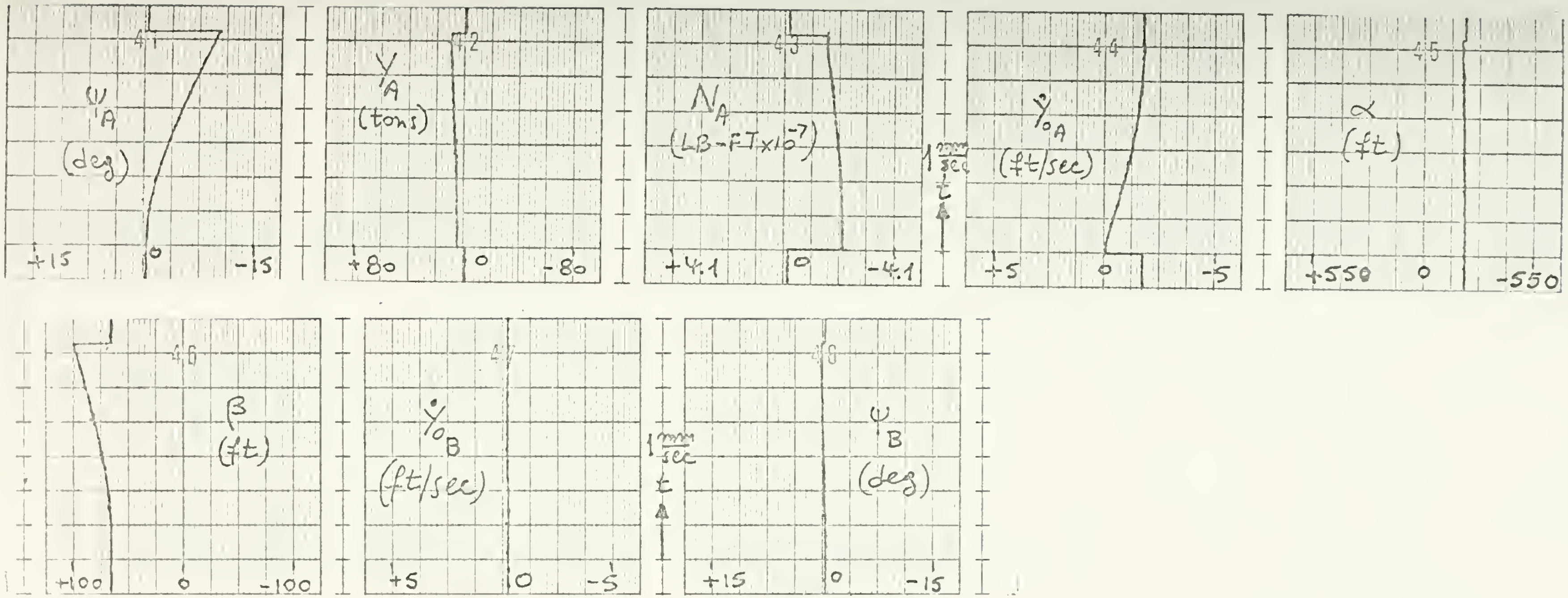


Figure 90. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=-200$ft, $\beta=70$ft)

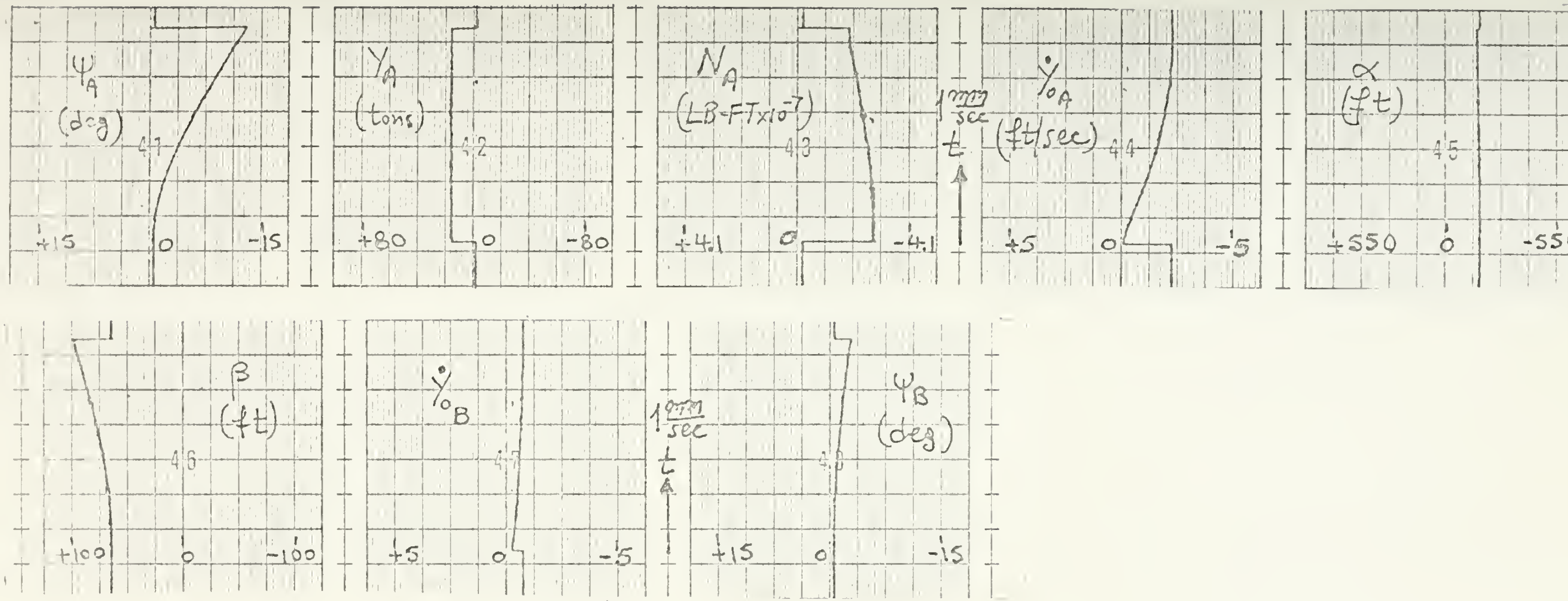


Figure 91. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=-160$ft, $\beta=70$ft)

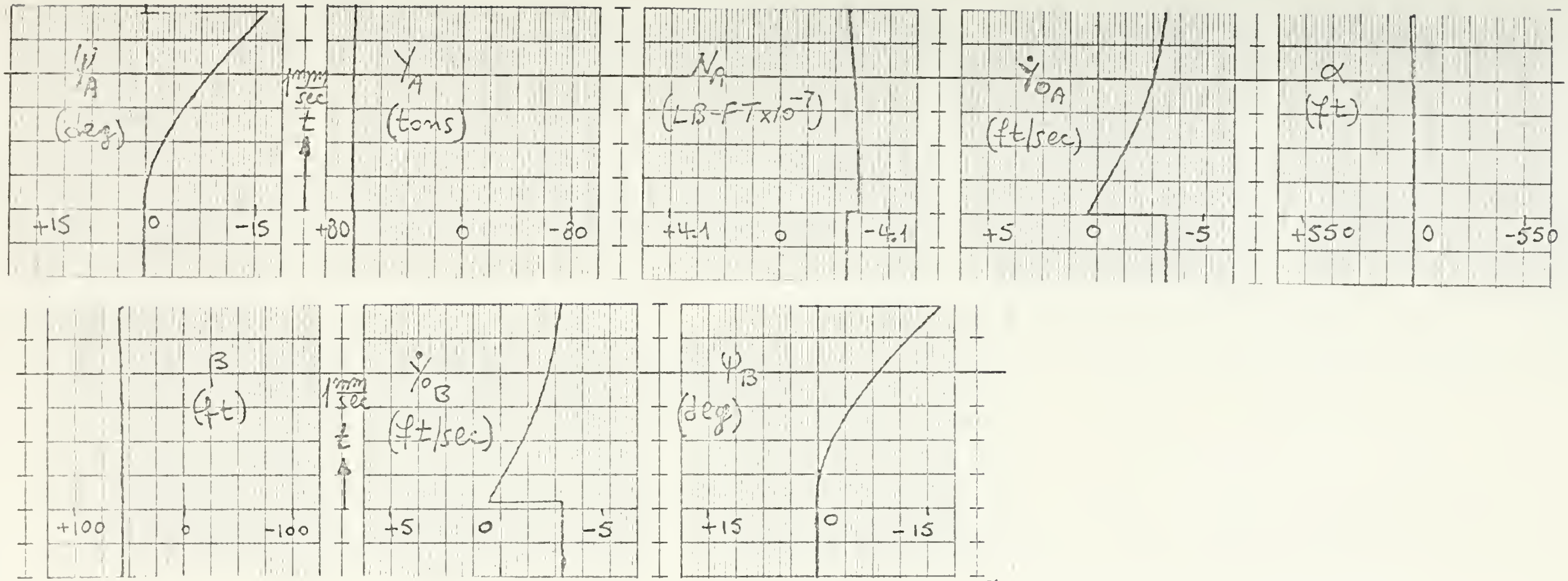


Figure 92. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=0$, $\beta=50$ft)

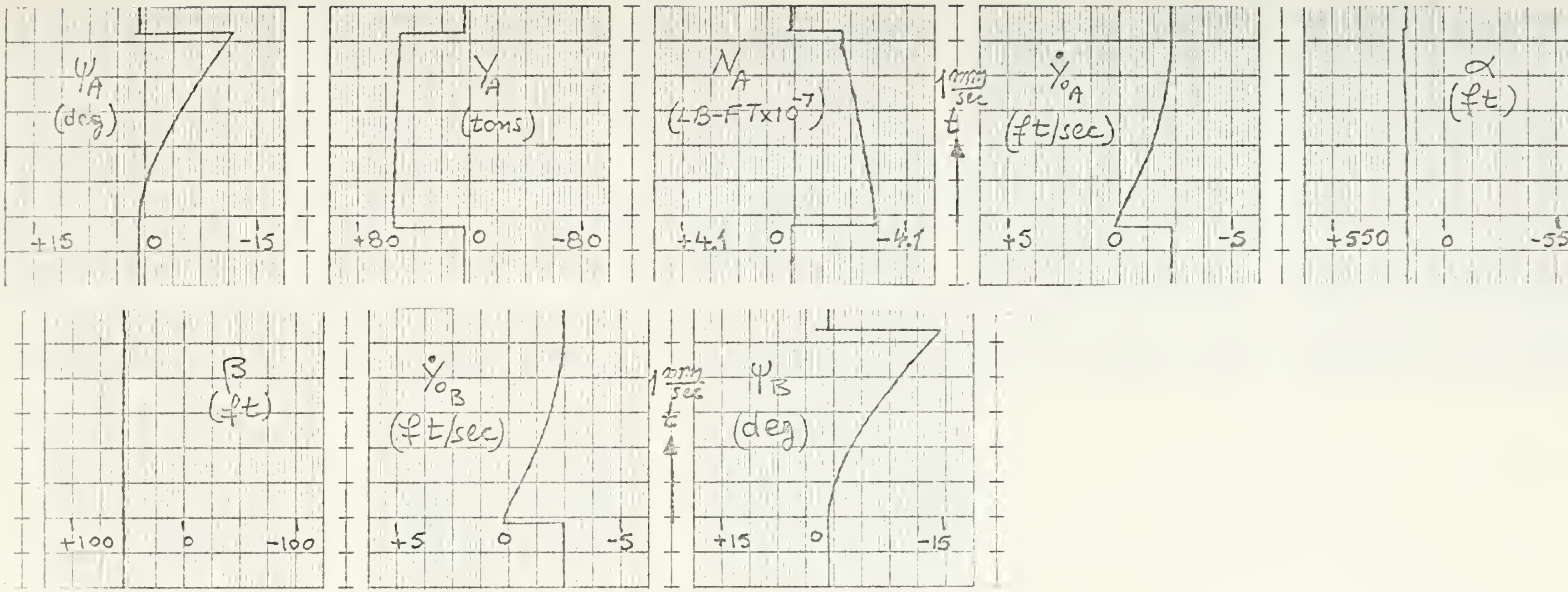


Figure 93a. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+100$ft, $\beta=50$ft)

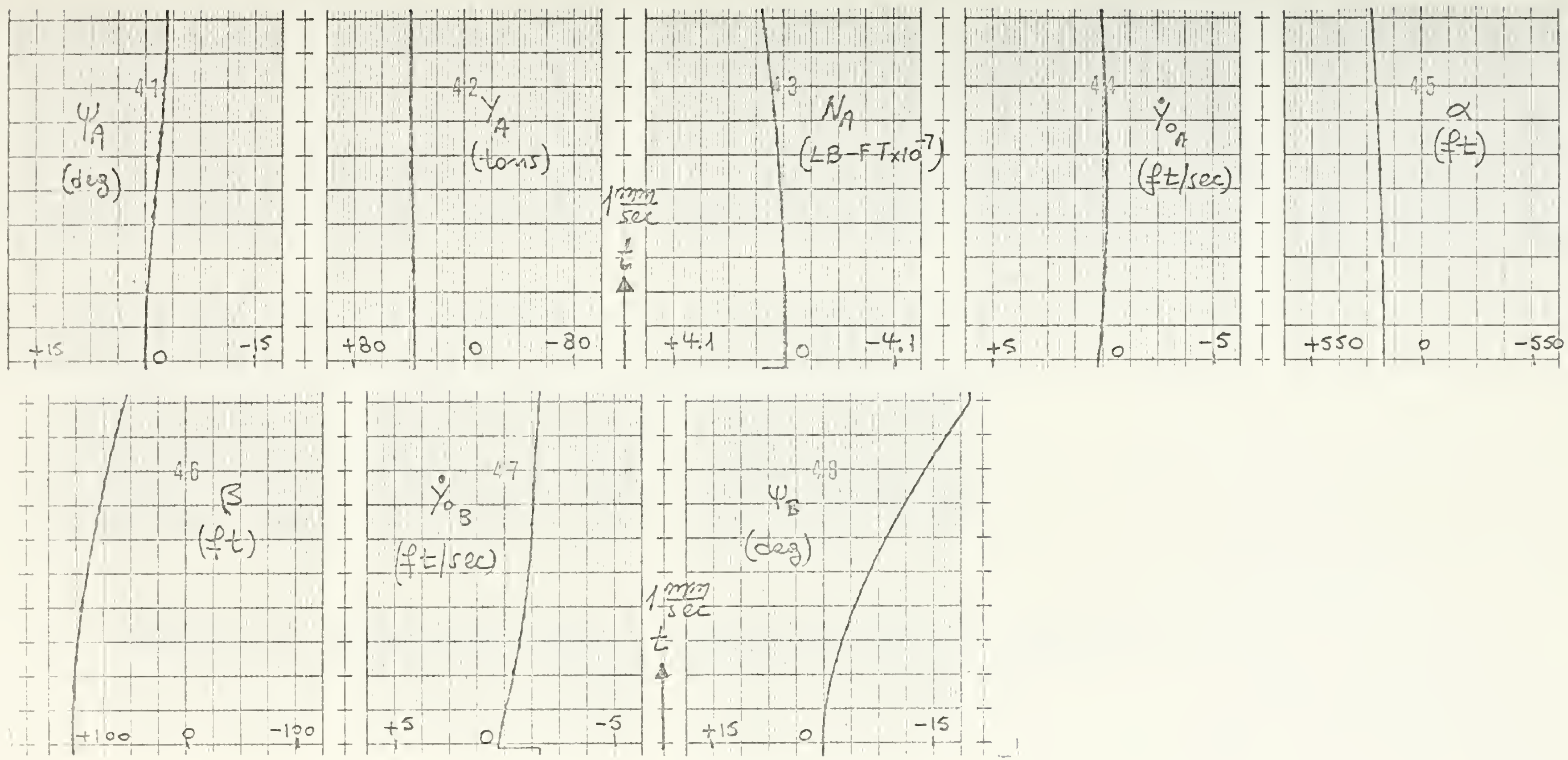


Figure 93b. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+160$ft, $\beta=100$ft)

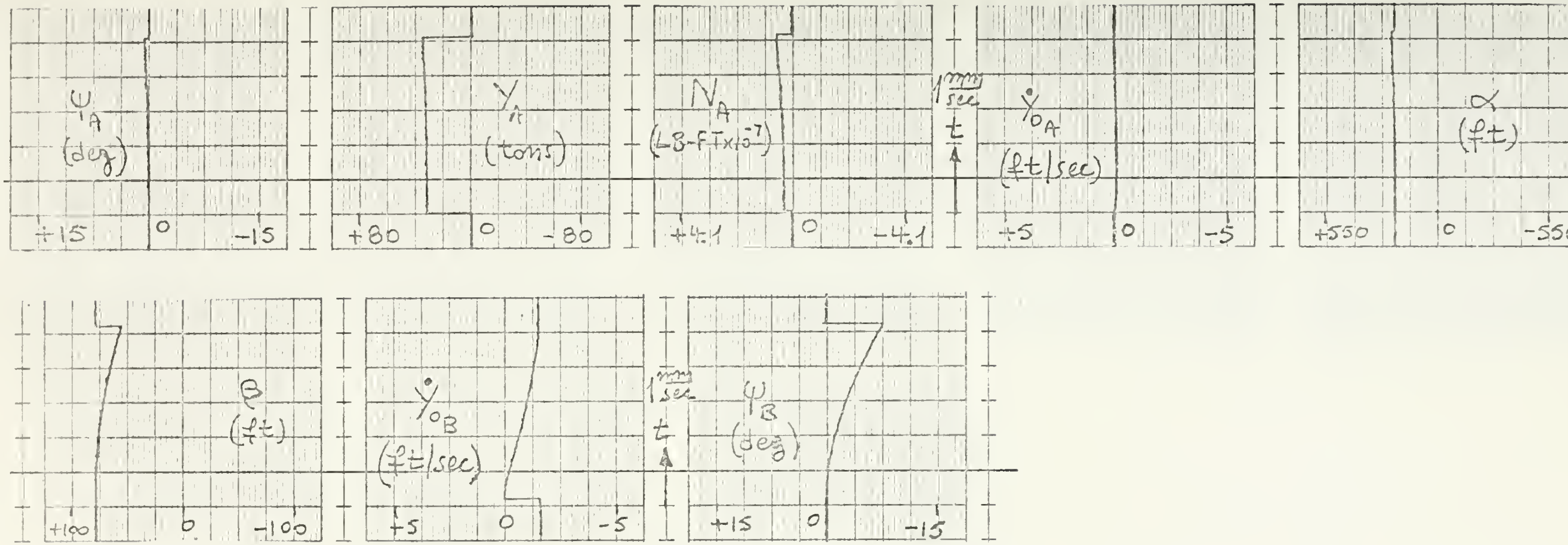


Figure 94. Linear response to interaction effects for Phase II.
($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+200$ft, $\beta=70$ft)

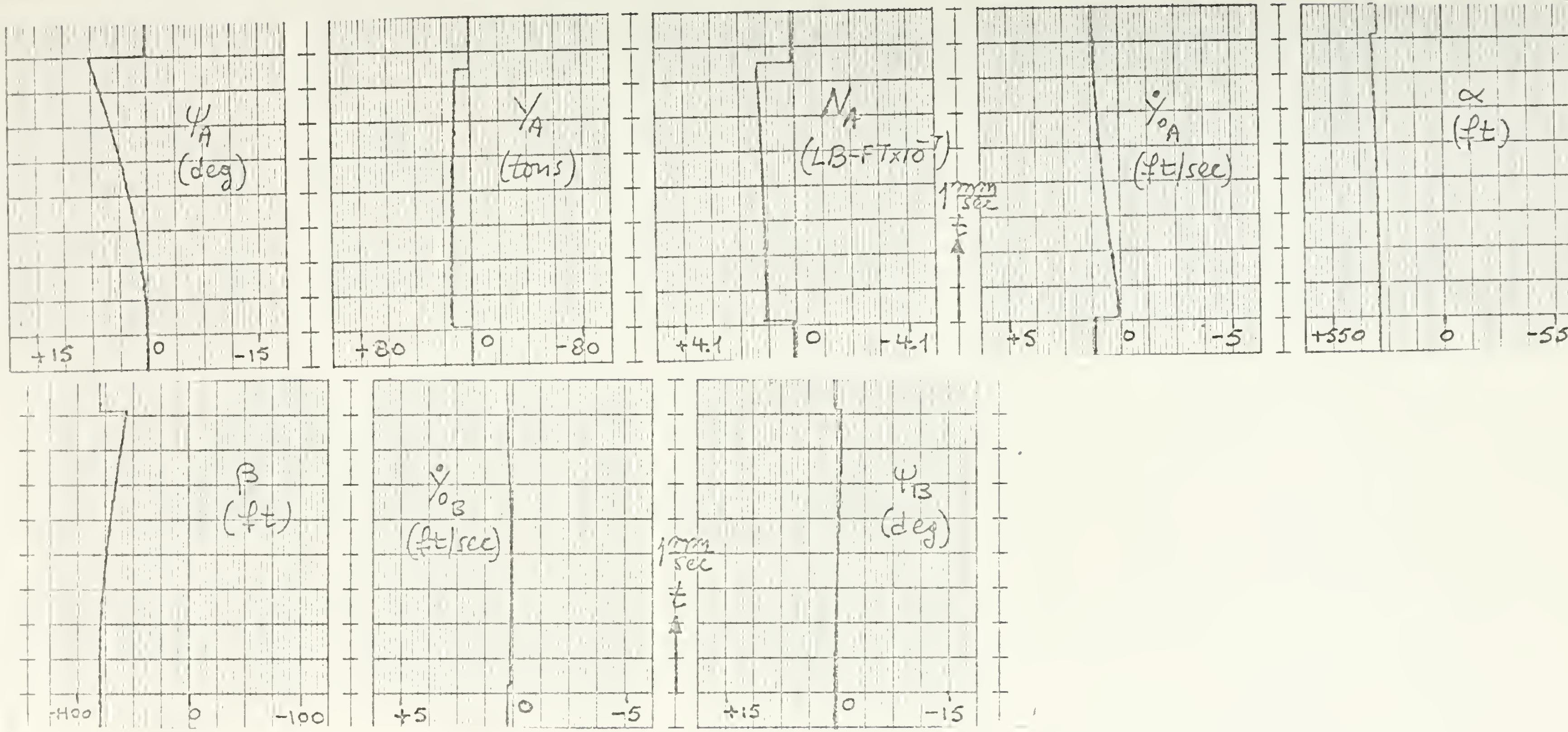


Figure 95. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+300$ft, $\beta=70$ft)

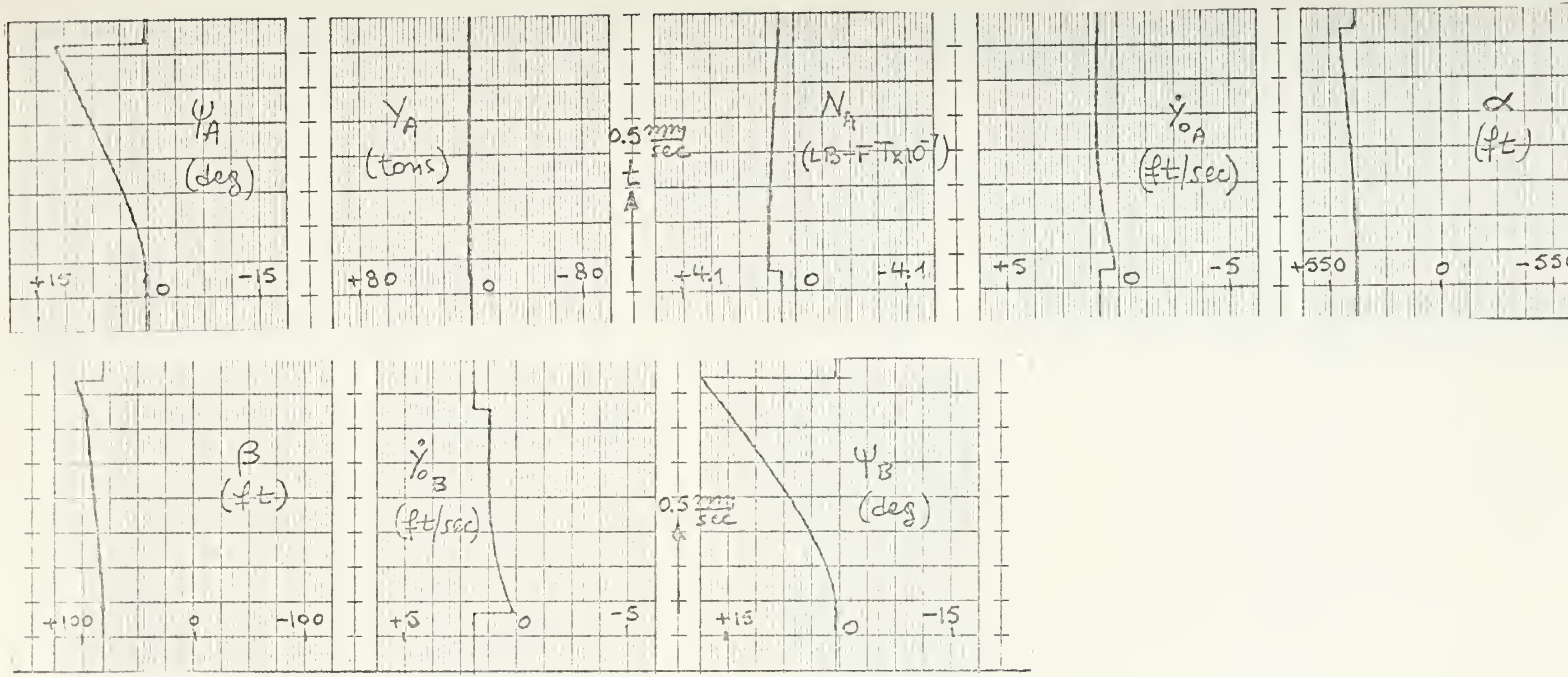


Figure 96. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+400$ft, $\beta=70$ft)

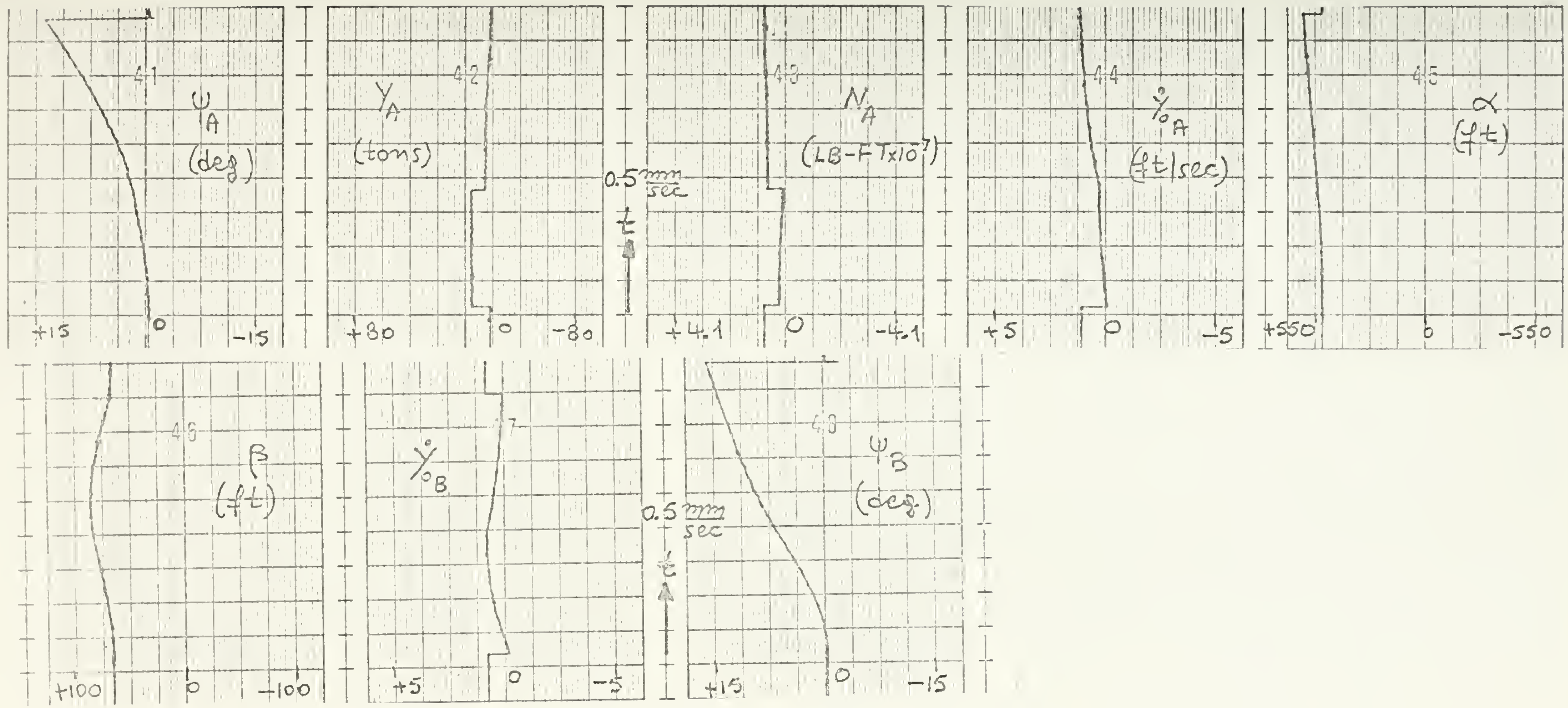


Figure 97. Linear response to interaction effects for Phase II. ($\Delta R=0$, $\delta n=+5$ RPM, initially $\alpha=+524$ft, $\beta=70$ft)

approximation it was possible to get the response of Figure 98 with control manually applied in terms of the perturbated parameters ψ_A, ΔR_A, N_A, $\dot{y}_{o_A}$, α, β, ΔR_B, ψ_B where A and B indices mean ship A and ship B respectively. The tracking ship originally placed at $x_o = -200$ ft, $y_o = 50$ ft has a 10 RPM greater propeller speed than the leading ship.

These responses do not give the actual needed rudder to maintain station and course unless the operator is practiced enough to know the behavior of both ships and hence is familiar with the amount of rudder actually needed. Nevertheless, these responses support the already known fact (from experience at sea) that underway replenishment is a controllable operation although experienced helmsmen are needed on both ships of the UNREP.

E. CONCLUSIONS - REMARKS - SUMMARY

Before any conclusion is derived it must be mentioned here that this study was done for the underway replenishment at sea of two equal sized merchant ships, namely MARINER class ships. The study also assumes calm water conditions which consequently assumes motion of ships in 3-degrees of freedom only. The hybrid simulation was done primarily for the no control plant although some remarks can be deduced for the nature of rudder (control surface) needed. Most of the observed results of this simulation study are already known from experience of real replenishment at sea operations. But this agreement assures that

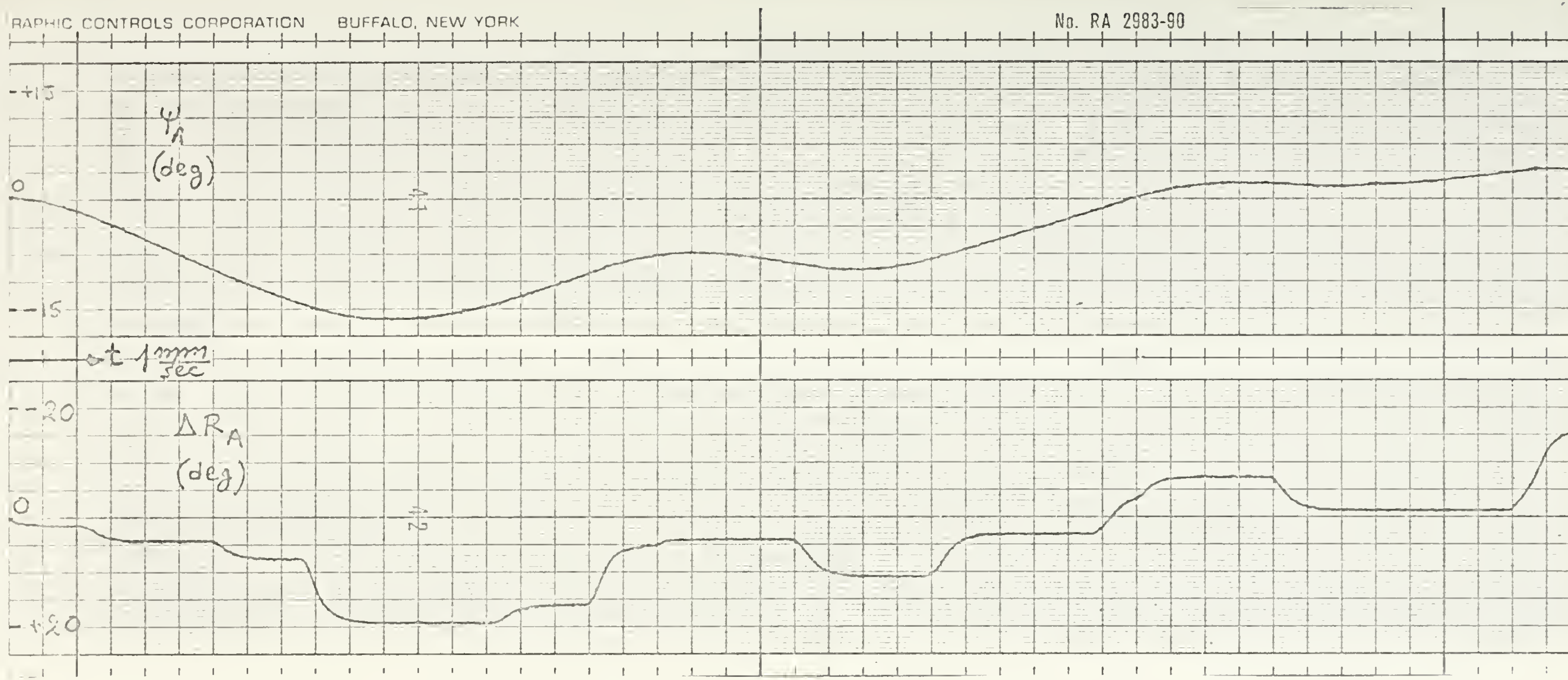


Figure 98-1. Linear response to interaction effects for Phase II.
(ΔR_A, ΔR_B, δn_B =+10 RPM, initially α=−200ft, β=50ft)

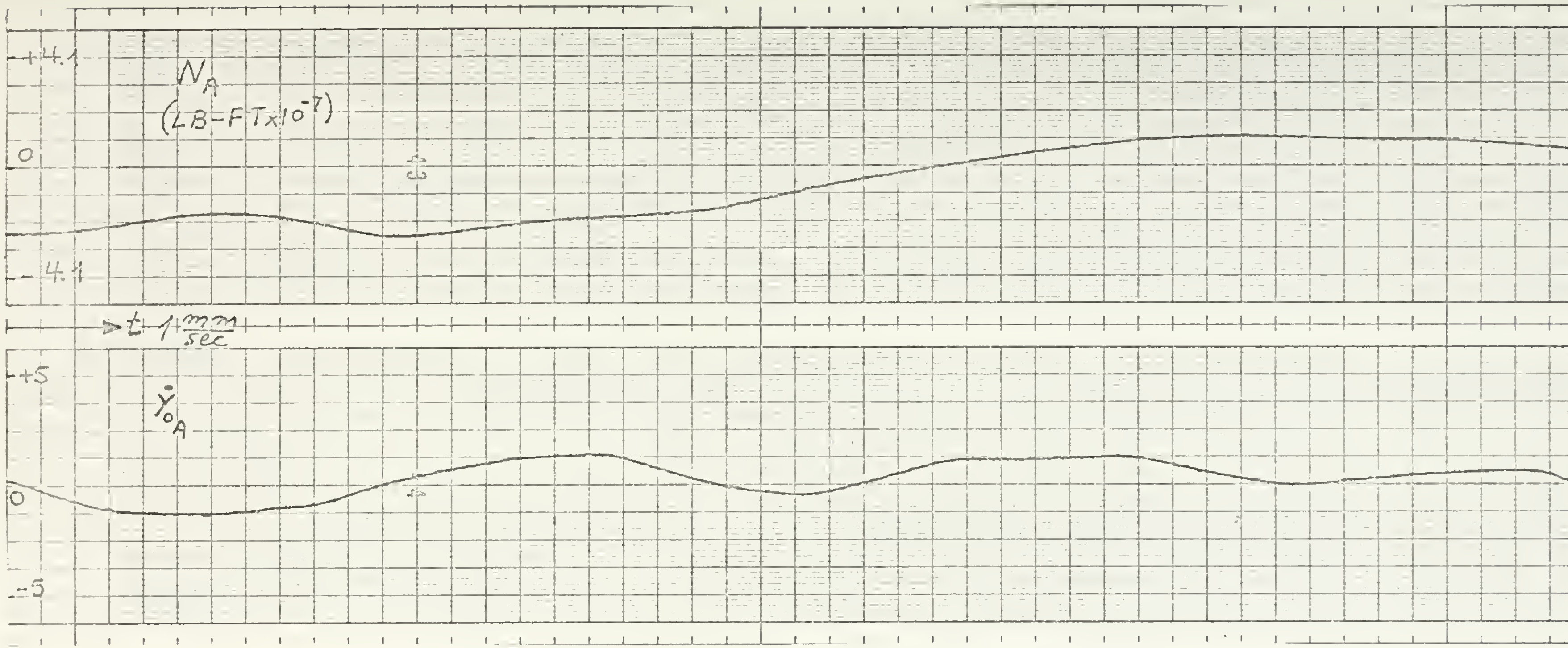


Figure 98–2. Linear response to interaction effects for Phase II. (ΔR_A, ΔR_B, δn_B=+10 RPM, initially α=–200ft, β=50ft)

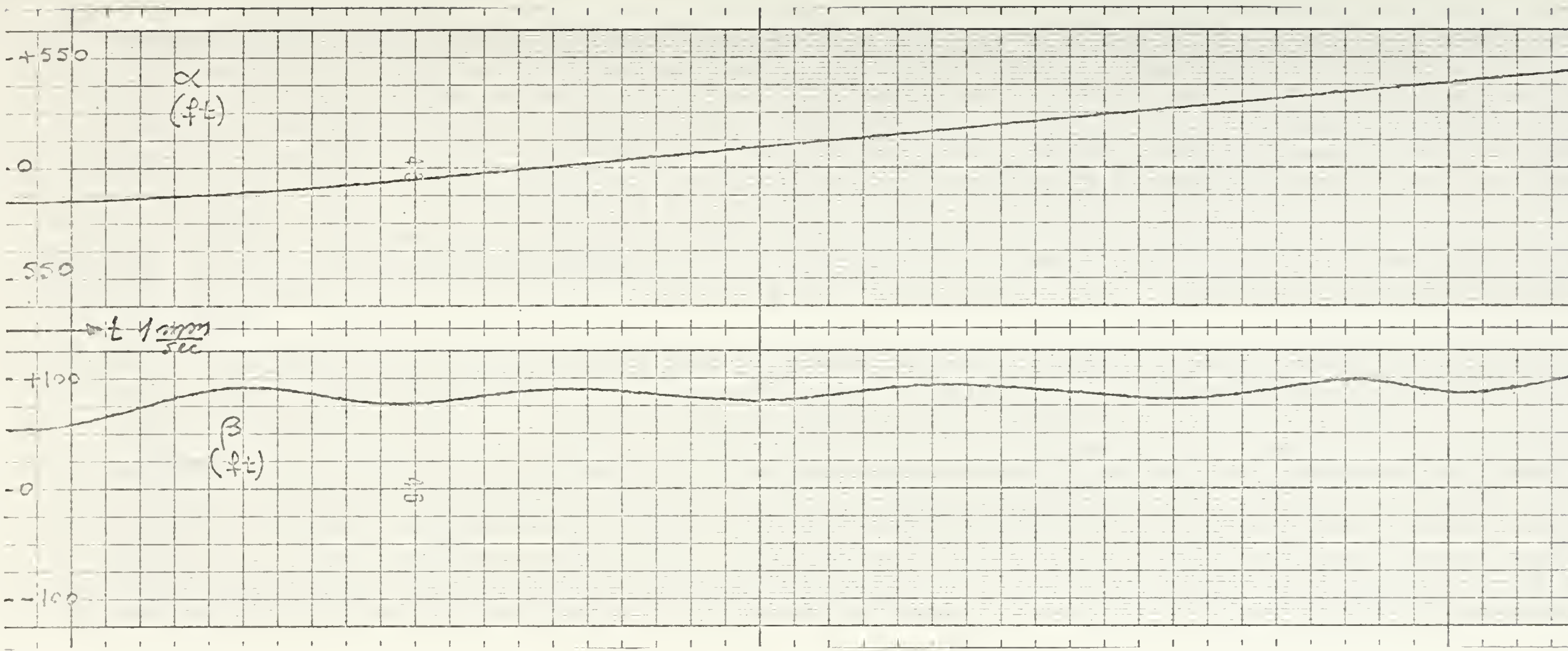


Figure 98-3. Linear response to interaction effects for Phase II.
(ΔR_A, ΔR_B, δn_B=+10 RPM, initially α=-200ft, β=50ft)

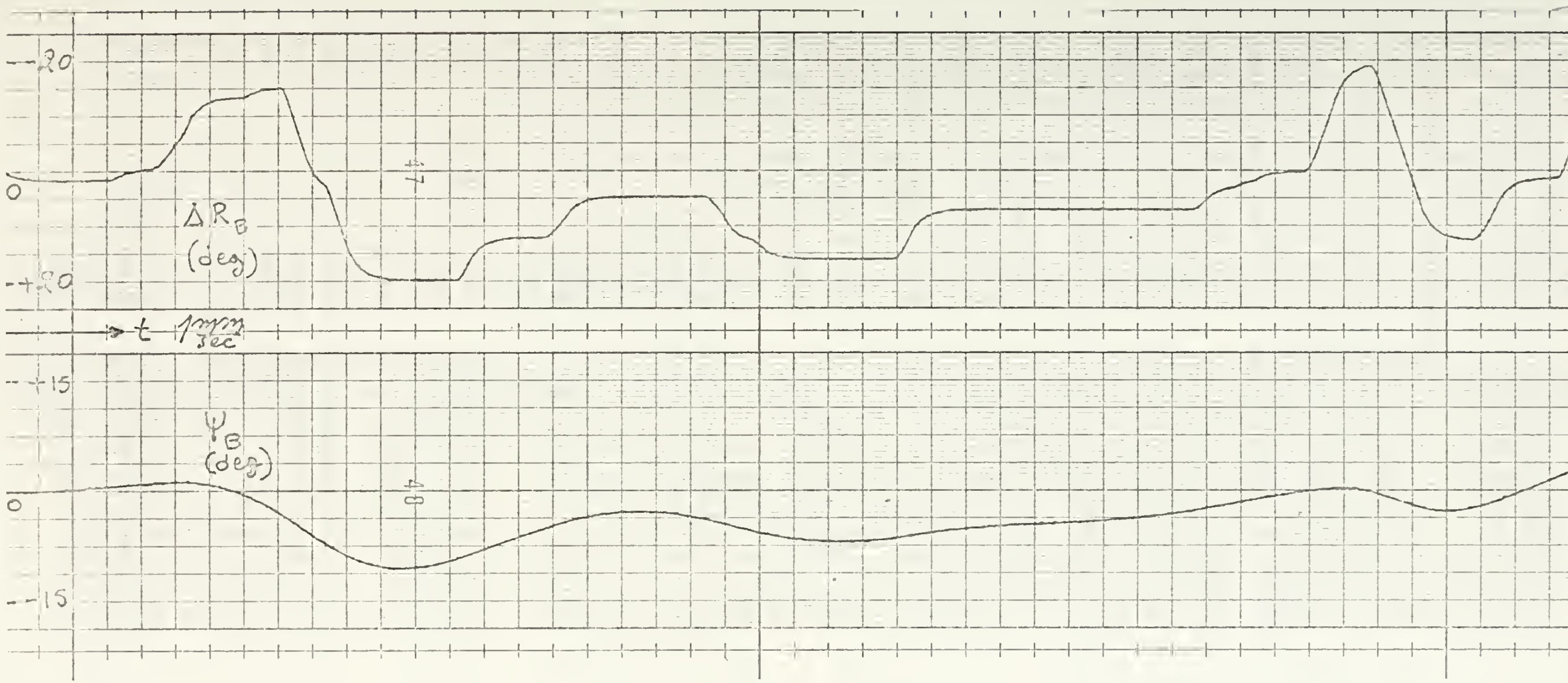


Figure 98–4. Linear response to interaction effects for Phase II. (ΔR_A, ΔR_B, δn_B=+10 RPM, initially α=−200ft, β=50ft)

this simulation was done correctly and gives the necessary background for the investigation and solution of the control problem.

During the approach and departure of the tracking ship there is a risk of collision since at these positions the lateral separation distance is decreased due to the interaction effects created from the pressure distribution fields of the hulls of both ships.

To be more specific, with the leading ship placed at (0,0) and having a 15 knots speed, i.e. the same speed with that of the space coordinate system, also with the tracking ship placed at (−524 ft, β) and having a Δn RPM greater propeller speed than that of the 15 knots ship the following can be deduced.

a. During the approach the stern of the leading ship and the bow of the tracking ship tend to attract, while the lateral distance is decreased until the longitudinal separation distance is roughly −250 ft. Also both ships yaw in the same direction, but at different rates and values depending on their speed difference.

b. For a decrease in longitudinal separation from −250 ft to zero ft the lateral separation increases although the ships yaw to different directions and values.

c. At zero longitudinal distance, i.e. exactly abeam position and 50 ft lateral distance both ships yaw negatively by the same amount while the lateral separation distance slightly increases throughout the time of recording.

d. With both ships having the same speed of 15 knots and being exactly abeam there is little change of the lateral distance throughout the time of recording although both yaw negatively.

e. During the departure from the exactly abeam position to until the longitudinal distance of roughly +350 ft.

   (1) A decrease of the lateral distance takes place.

   (2) Initially the bow of the leading ship tends to be attracted to the stern of the tracking ship, while both ships yaw negatively at different angles.

   (3) At roughly +250 ft longitudinal separation distance the leading ship changes direction of yawing while the tracking ship maintains negative yawing. This tends to bring the stern of the tracking ship towards the leading ship.

f. For longitudinal separation distances greater than roughly 350 ft, the lateral distance increases while both ships yaw positively at different angles and rates.

One basic assumption was carried out throughout the UNREP simulation. That is both ships could be initially placed at any desired position.

From the above discussion it is seen that the best position for station keeping and collision avoiding for two ships of the same size is while keeping the same speed exactly abeam, although a certain amount of rudder has to be applied on both ships for course keeping. This is in agreement with reference [1]. It is obvious that during the departure and approach the rudder to be applied must counteract both the interaction moment as well as create a yaw angle sufficient to counteract both the attraction force and the rudder force. By these means collision should be avoided provided that there is enough initial

lateral separation distance so the time elapsed between the instant action is applied by the operator (helmsman) and rudder action takes place is adequate. It can be seen also that during the approach and departure both ships yaw from positive to negative angles and vice versa. This implies that in a short period of time the operator has to apply negative to positive rudder angle provided that the operator has been trained enough so that he knows the exact time at which rudder has to be applied. Obviously this is not easy.

This study probably would be more effective using the interactive graphics available on modern computer systems.

A matter of future investigation should be the implementation of automatic controls in the hybrid simulation as well as the inclusion of sea states.

VII. INVESTIGATION OF THE CONTROL PROBLEM

The leading ship usually is responsible for course keeping and the tracking ship is responsible for both course and station keeping. These requirements imply two different controls for the course and the station or distance keeping.

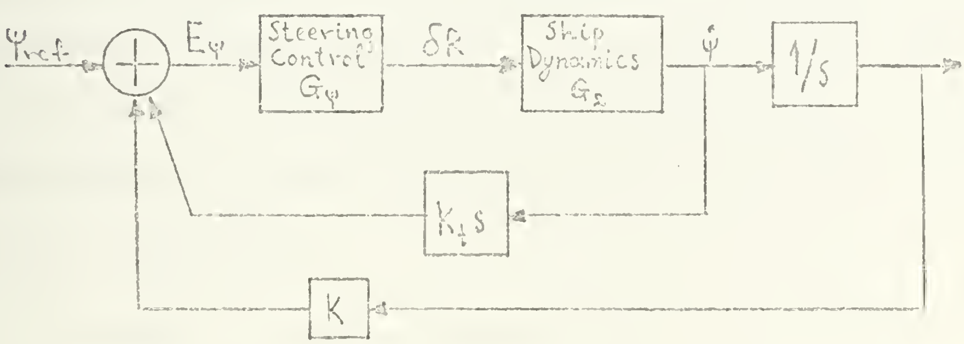


Figure 99. Course keeping loop.

A. COURSE KEEPING LOOP

Figure 99 shows the control loop for course keeping. The steering control block G_ψ can be represented as a first order lag function. In the section B2 the time lag was estimated to be of the order of 8 sec. Hence the transfer function should be as follows:

$$G_\psi = \frac{K_\delta}{S + \frac{1}{8}}$$

where K_δ is the steering control gain.

The course keeping loop may not contain the yaw angle reference, ψ_{ref}, since during the UNREP operation course changing is not desired but course keeping. Hence for the beginning at least of the simulation with automatic control included the reference yaw angle ψ_{ref} should be set equal to zero. The ships dynamics block contains the transfer function $G_2 = \frac{\delta R}{\psi}$ which can be found by Laplace transforming equations (V-1) and solving for the above mentioned ratio. It should be noted here that both the transfer function G_ψ and G_2 have been built for the analog simulation of Phase I and II. Obviously in question must be the order of magnitude of the feedback gains K_t and K. The values of K_t and K can be designed by normal feedback control techniques.

B. DISTANCE OR STATION KEEPING LOOP

Figure 100 shows the distance keeping loop where β_{ref} is the ordered lateral separation distance and β the actual lateral distance between the two ships. Note that this

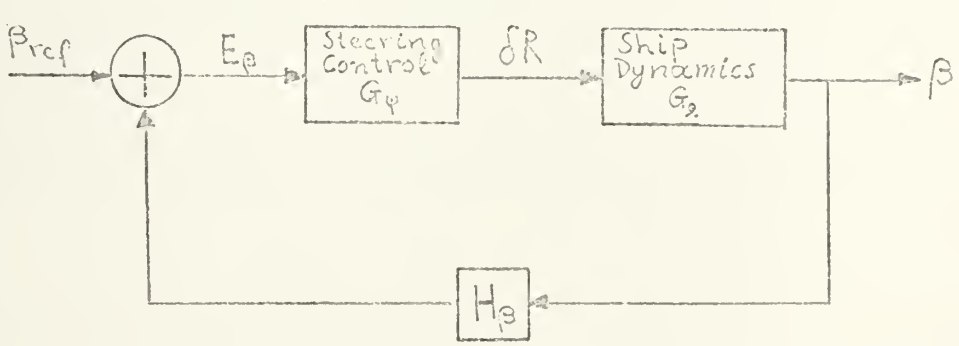


Figure 100. Distance keeping loop.

control loop contains the ships dynamics G_2 including hybrid simulation for obtaining the lateral distance.

In question must be whether the feedback function should contain the rate of change as well as the change of the lateral distance. The steering control transfer function is again:

$$G_\psi = \frac{K_\delta}{S + \frac{1}{8}}$$

Note that for the distance keeping loop the ships dynamics transfer function G_2 involves hybrid simulation since transformation of coordinates is implied for the quantities being measured with respect to the space coordinates system.

COMPUTER PROGRAM IA

```
*
*
*
*     STATIC TEST FOR SHIP NO 1
¬JOB GAL1225
¬FORTRAN LS,GO
C   SECTION CHECKING POT AND AMP VALUES FOR SHIP #1
      DIMENSION POTAD(30),POTVAL(30),AMPAD(30),AMPVAL(30)
      INTEGER POTAD,AMPAD
      DATA N/26/
      READ(5,100) (POTAD(I),POTVAL(I),I=1,N)
  100 FORMAT(A4,F10.4)
      DO 10 I=1,N
   10 CALL SETPOT(POTAD(I),POTVAL(I))
      WRITE(6,101) (POTAD(I),POTVAL(I),I=1,N)
  101 FORMAT(A4,F10.4)
      READ(5,102) (AMPAD(I),I=1,28)
  102 FORMAT(A4)
      CALL RESET(1000)
      DO 12 I=1,28
   12 CALL SCAN(AMPAD(I),AMPVAL(I))
      WRITE(6,103) (AMPAD(I),AMPVAL(I),I=1,28)
  103 FORMAT(A4,F10.6)
      DO 20 I=1,N
   20 CALL SCAN(POTAD(I),POTVAL(I))
      WRITE(6,200)(POTAD(I),POTVAL(I),I=1,N)
  200 FORMAT(A4,F10.6)
      END
¬LOAD XR,MAP
¬DATA
P000  0.1000
P001  0.0300
P002  0.0803
P003  0.0600
P004  0.0404
P005  0.0052
P006  0.1660
P007  0.0900
P010  0.2379
P011  0.2383
P012  0.4717
P013  0.0250
P014  0.1200
P015  0.5607
P016  0.1340
P017  0.1500
P020  0.0920
P021  0.0097
P022 0.3576
P053  0.0905
P054  0.0500
P055 0.1497
P0500.0337
P051  0.3000
P056  0.0092
P057  0.4540
A001
A003
A005
A013
A017
D001
D003
D005
D013
D017
A006
A016
A002
A010
A014
```

A022
A203
A112
A201
A050
A056
A052
A060
A212
A051
A057
D051
D057

COMPUTER PROGRAM IB

```
*
*
*
*      STATIC TEST FOR SHIP NO 2
¬JOB GAL1225
¬FORTRAN LS,GO
C   SECTION CHECKING POT AND AMP VALUES FOR SHIP #2
       DIMENSION POTAD(30),POTVAL(30),AMPAD(30),AMPVAL(30)
       INTEGER POTAD,AMPAD
       DATA N/22/
       READ(5,100) (POTAD(I),POTVAL(I),I=1,N)
   100 FORMAT(A4,F10.4)
       DO 10 I=1,N
    10 CALL SETPOT(POTAD(I),POTVAL(I))
       WRITE(6,101) (POTAD(I),POTVAL(I),I=1,N)
   101 FORMAT(A4,F10.4)
       READ(5,102) (AMPAD(I),I=1,27)
   102 FORMAT(A4)
       CALL RESET(1000)
       DO 12 I=1,27
    12 CALL SCAN(AMPAD(I),AMPVAL(I))
       WRITE(6,103) (AMPAD(I),AMPVAL(I),I=1,27)
   103 FORMAT(A4,F10.6)
       DO 20 I=1,N
    20 CALL SCAN(POTAD(I),POTVAL(I))
       WRITE(6,200)(POTAD(I),POTVAL(I),I=1,N)
   200 FORMAT(A4,F10.6)
       END
¬LOAD  XR,MAP
¬DATA
P024   0.1000
P025   0.0300
P026   0.0803
P027   0.0600
P030   0.0404
P045   0.0920
P031   0.0052
P023   0.0905
P034   0.1660
P033   0.0900
P046   0.4717
P032   0.2379
P035   0.2383
P047   0.1497
P036   0.0097
P037   0.0250
P040   0.1200
P041   0.1340
P042   0.1500
P043   0.5607
P044   0.3576
P052   0.5000
A035
D035
A027
D027
A033
D033
A041
D041
A043
D043
A034
A036
A026
A044
A030
A042
A104
A065
D065
```

A061
D061
A072
A076
A066
A204
A211
A214

COMPUTER PROGRAM III

```
*
*
*
*     LINEAR INTERPOLATION IN 2-DIMENSIONS ARRAY CF N-MOMENT
*     AND Y-FORCE
¬JOB GAL1225
¬FORTRAN LS,GO
      REAL NMAX,NDIM,NSCAL
      REAL NBAR,N,NBAR1
      DIMENSION Y(30,30),N(30,30)
C STORAG OF NONDIMENSIONAL ARRAY FOR N AND Y
      DO 10 J=1,25
   10 READ(5,100) (Y(J,I),I=1,6)
  100 FORMAT(6E11.4)
      DO 12 J=1,25
   12 READ(5,100) (N(J,I),I=1,6)
      WRITE(6,200)
  200 FORMAT(' ','THIS IS Y(J,I)',//)
      DO 11J=1,25
      WRITE (6,201) (Y(J,I),I=1,6)
  201 FORMAT(' ',10X,6(E11.4,2X),//)
   11 CONTINUE
      WRITE(6,300)
  300 FORMAT(' ','THIS IS N(J,I)',//)
      DO 13 J=1,25
      WRITE(6,301) (N(J,I),I=1,6)
  301 FORMAT(' ',10X,6(E11.4,2X),//)
   13 CONTINUE
C INTERPOLATION IN 2-DIM. ARRAY.PASS BETBAR AND ALPBAR
C REMEMBER BETBAR=1.0 CORRESPONDS BETA=100.0 FEET***
C ALPBAR=1.0 CORRESPONDS ALPHA=550.0 FEET
C ALSO BETBAR AND ALPBAR ARE PAST IN COMPUTER UNITS
      READ(5,400)ALPBAR,BETBAR
  400 FORMAT(2F11.6)
      WRITE(6,401)
  401 FORMAT(' ',10X,'THIS IS ALPBAR-BETBAR',//)
      WRITE(6,402) ALPBAR,BETBAR
  402 FORMAT(' ',10X,2F11.6)
C RESCALING OF ALPHABAR=ALPBAR AND BETABAR=BETBAR
      ALPHA=550.0*ALPBAR
      WRITE(6,403)
  403 FORMAT(' ',10X,'THIS IS ALPHA',//)
      WRITE(6,501)ALPHA
      BETBA=ABS(BETBAR)
      BETA=100.0*BETBA
      WRITE(6,404)
  404 FORMAT(' ',10X,'THIS IS BETA',//)
      WRITE(6,501)BETA
      IF(BETA.LT.50.0) GO TO 803
      IF(BETA.GT.100.0) GO TO 801
      IF(ALPHA.LT.-550.0) GO TO 801
      IF(ALPHA.GT.550.0) GO TO 801
      GO TO 800
  801 NBAR=0.0
      YBAR=0.0
      GO TO 802
C SEARCH FOR INDETIFICATION OF ARRAY ELEMENT
C FIND CORRESPONDED Y AND N -LINEAR INTERPOLATION IN 2-DIMEN
  800 IB1=BETA/10.0
      IB=IB1-4
      BETA1=IB1*10
      WTB=(BETA-BETA1)/10.0
      IF(ALPHA.LT.0.0) GO TO 1
      IF(ALPHA.GT.0.0) GO TO 2
C ALPHA =0
      IA=13
      WTA=0.0
      GO TO 3
C ALPHA LESS THAN ZERO
    1 IA1=-ALPHA/50.0
      ALPHA1=-IA1*50
```

```
      WTA=-(ALPHA-ALPHA1)/50.0
      IA=13-IA1
      GC TO 3
C ALPHA GREATER THAN ZERO
    2 IA1=ALPHA/50.0
      IA=13+IA1
      ALPHA1=IA1*50
      WTA=(ALPHA-ALPHA1)/50.0
    3 IB2=IB+1
      IF(IB.EQ.6) IB2=6
      IA2=IA+1
      IF(IA.EQ.25) IA2=25
      WRITE(6,101) IB1,IB,IB2,IA1
  101 FORMAT(' ',10X,'IB1=',I3,5X,'IB=',I3,5X,'IB2=',I3,5X,'
      WRITE(6,102) IA,IA2
  102 FORMAT(' ',10X,'IA=',I3,5X,'IA2=',I3,//)
      WRITE(6,202) BETA1,WTB,ALPHA1
  202 FORMAT(' ','BETA1',E14.8,2X,'WTB',E14.8,2X,'ALPHA1',E1
      WRITE(6,203) WTA
  203 FORMAT(' ','WTA=',E14.8,//)
      IF(ALPHA.LT.0.0) IA2=IA-1
      IF(IA.EQ.1) IA2=1
      IF(WTA.EQ.0.0)IA2=IA
      IF(WTB.EQ.0.0) IB2=IB
      NBAR1=N(IA,IB2)
      WRITE(6,602)
  602 FORMAT(' ','THIS IS NBAR1',//)
      WRITE(6,502) NBAR1,IA,IB2
      NBAR=N(IA,IB)
      WRITE(6,603)
  603 FORMAT(' ','THIS IS NBAR',//)
      WRITE(6,502) NBAR,IA,IB
      BARN1=(NBAR1-NBAR)*WTB+NBAR
      WRITE(6,604)
  604 FORMAT(' ','THIS IS BARN1',//)
      WRITE(6,501) BARN1
      NBAR1=N(IA2,IB2)
      WRITE(6,605)
  605 FORMAT(' ','THIS IS NBAR1',//)
      WRITE(6,502) NBAR1,IA2,IB2
      NBAR=N(IA2,IB)
      WRITE(6,606)
  606 FORMAT(' ','THIS IS NBAR',//)
      WRITE(6,502) NBAR,IA2,IB
      BARN2=(NBAR1-NBAR)*WTB+NBAR
      WRITE(6,607)
  607 FORMAT(' ','THIS IS BARN2',//)
      WRITE(6,501) BARN2
      NBAR=(BARN2-BARN1)*WTA+BARN1
      WRITE(6,500)
  500 FORMAT(' ','THIS IS FINAL NBAR',//)
      WRITE(6,501) NBAR
  501 FORMAT(' ',10X,E14.8,//)
      YBAR1=Y(IA,IB2)
      WRITE(6,608)
  608 FORMAT(' ','THIS IS YBAR1',//)
      WRITE(6,502) YBAR1,IA,IB2
      YBAR=Y(IA,IB)
      WRITE(6,609)
  609 FORMAT(' ','THIS IS YBAR',//)
      WRITE(6,502) YBAR,IA,IB
      BARY1=(YBAR1-YBAR)*WTB+YBAR
      WRITE(6,610)
  610 FORMAT(' ','THIS IS BARY1',//)
      WRITE(6,601)BARY1
      YBAR1=Y(IA2,IB2)
      WRITE(6,611)
  611 FORMAT(' ','THIS IS YBAR1',//)
      WRITE(6,502) YBAR1,IA2,IB2
      YBAR=Y(IA2,IB)
      WRITE(6,612)
  612 FORMAT(' ','THIS IS YBAR',//)
```

```
      WRITE(6,502) YBAR,IA2,IB
      BARY2=(YBAR1-YBAR)*WTB+YBAR
      WRITE(6,613)
  613 FORMAT(' ','THIS IS BARY2',//)
      WRITE(6,601) BARY2
      YBAR=(BARY2-BARY1)*WTA+BARY1
      WRITE(6,600)
  600 FORMAT(' ','THIS IS FINAL YBAR',//)
      WRITE(6,601) YBAR
  601 FORMAT(' ',10X,E14.8,//)
  502 FORMAT(' ',10X,E14.8,5X,'ROW=',I3,1X,'COL=',I3)
C REMEMBER SIMULATION IS DONE IN COMPUTER UNITS SO NO NEED T
C**** DIVIDE BY 100.0 SINCE SUBR. DAC CONVERTS BY ITSELF IN
      GO TO 2000
  803 NBAR=44.5E-05
      WRITE(6,500)
      WRITE(6,501) NBAR
      YBAR=90.0E-05
      WRITE(6,600)
      WRITE(6,601) YBAR
      GO TO 2000
  802 WRITE(6,500)
      WRITE(6,501) NBAR
      WRITE(6,600)
      WRITE(6,601) YBAR
 2000 END
¬LOAD XR,MAP
¬DATA
*
*
*
*                        THIS IS Y ARRAY
*
*
*
-0.1400E-03-0.1263E-03-0.1160E-03-0.1058E-03-0.9753E-04-0.90
-0.2400E-03-0.2112E-03-0.1897E-03-0.1681E-03-0.1508E-03-0.13
-0.3200E-03-0.2762E-03-0.2433E-03-0.2104E-03-0.1841E-03-0.16
-0.3800E-03-0.3225E-03-0.2793E-03-0.2362E-03-0.2016E-03-0.17
-0.4000E-03-0.3337E-03-0.2840E-03-0.2342E-03-0.1945E-03-0.15
-0.3500E-03-0.2870E-03-0.2397E-03-0.1925E-03-0.1547E-03-0.12
-0.2600E-03-0.2079E-03-0.1689E-03-0.1299E-03-0.9863E-04-0.70
-0.1300E-03-0.9384E-04-0.6671E-04-0.3959E-04-0.1789E-04 0.20
 0.4000E-04 0.5507E-04 0.6637E-04 0.7767E-04 0.8671E-04 0.95
 0.2700E-03 0.2508E-03 0.2364E-03 0.2221E-03 0.2105E-03 0.20
 0.5000E-03 0.4507E-03 0.4137E-03 0.3767E-03 0.3471E-03 0.32
 0.7000E-03 0.6225E-03 0.5643E-03 0.5062E-03 0.4596E-03 0.41
 0.8500E-03 0.7500E-03 0.6750E-03 0.6000E-03 0.5400E-03 0.48
 0.9000E-03 0.7844E-03 0.6977E-03 0.6110E-03 0.5416E-03 0.47
 0.8200E-03 0.7159E-03 0.6378E-03 0.5597E-03 0.4973E-03 0.44
 0.6250E-03 0.5579E-03 0.5075E-03 0.4572E-03 0.4169E-03 0.38
 0.4500E-03 0.4089E-03 0.3781E-03 0.3473E-03 0.3226E-03 0.30
 0.3000E-03 0.2781E-03 0.2616E-03 0.2452E-03 0.2321E-03 0.22
 0.1700E-03 0.1673E-03 0.1652E-03 0.1632E-03 0.1615E-03 0.16
 0.6000E-04 0.6822E-04 0.7438E-04 0.8055E-04 0.8548E-04 0.90
-0.2000E-04-0.3562E-05 0.8767E-05 0.2110E-04 0.3096E-04 0.40
-0.5000E-04-0.3493E-04-0.2363E-04-0.1233E-04-0.3288E-05 0.50
-0.6000E-04-0.4904E-04-0.4082E-04-0.3260E-04-0.2603E-04-0.20
-0.5000E-04-0.4699E-04-0.4473E-04-0.4247E-04-0.4065E-04-0.39
-0.1000E-04-0.2096E-04-0.2918E-04-0.3740E-04-0.4397E-04-0.50
*
*
*
*                        THIS IS N ARRAY
*
*
*
 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.60
 0.1100E-03 0.1036E-03 0.9786E-04 0.9280E-04 0.8890E-04 0.85
 0.1390E-03 0.1278E-03 0.1176E-03 0.1087E-03 0.1019E-03 0.95
 0.1530E-03 0.1349E-03 0.1186E-03 0.1042E-03 0.9308E-04 0.82
 0.1400E-03 0.1197E-03 0.1012E-03 0.8497E-04 0.7249E-04 0.60
```

0.7000E-04	0.5728E-04	0.4572E-04	0.3561E-04	0.2780E-04	0.20
-0.5000E-04	-0.4618E-04	-0.4272E-04	-0.3968E-04	-0.3734E-04	-0.35
-0.1750E-03	-0.1536E-03	-0.1342E-03	-0.1172E-03	-0.1041E-03	-0.91
-0.3000E-03	-0.2598E-03	-0.2238E-03	-0.1913E-03	-0.1667E-03	-0.14
-0.4100E-03	-0.3528E-03	-0.3008E-03	-0.2552E-03	-0.2201E-03	-0.18
-0.4420E-03	-0.3880E-03	-0.3294E-03	-0.2824E-03	-0.2462E-03	-0.21
-0.4350E-03	-0.3785E-03	-0.3272E-03	-0.2823E-03	-0.2476E-03	-0.21
-0.3740E-03	-0.3300E-03	-0.2900E-03	-0.2550E-03	-0.2280E-03	-0.20
-0.2800E-03	-0.2520E-03	-0.2266E-03	-0.2043E-03	-0.1872E-03	-0.17
-0.1500E-03	-0.1373E-03	-0.1257E-03	-0.1156E-03	-0.1078E-03	-0.10
-0.4500E-03	-0.4373E-04	-0.4257E-04	-0.4156E-04	-0.4078E-04	-0.40
0.4200E-04	0.3640E-04	0.3132E-04	0.2687E-04	0.2343E-04	0.20
0.1100E-03	0.9728E-04	0.8572E-04	0.7561E-04	0.6780E-04	0.60
0.1400E-03	0.1247E-03	0.1109E-03	0.9873E-04	0.8936E-04	0.80
0.1320E-03	0.1193E-03	0.1077E-03	0.9761E-04	0.8980E-04	0.82
0.1200E-03	0.1060E-03	0.9329E-04	0.8217E-04	0.7358E-04	0.65
0.1020E-03	0.8750E-04	0.7432E-04	0.6279E-04	0.5390E-04	0.45
0.7500E-04	0.6355E-04	0.5315E-04	0.4405E-04	0.3702E-04	0.30
0.4500E-04	0.3864E-04	0.3286E-04	0.2780E-04	0.2390E-04	0.20
0.9000E-05	0.1053E-04	0.1191E-04	0.1313E-04	0.1406E-04	0.15

COMPUTER PROGRAM IVA

```
*
*
*
*     COORDINATES TRANSFORMATICN FOR SHIP NO 1
¬JOB GAL1225
¬ASSIGN 6=NO
¬FORTRAN LS,GO
C  SECTION CHECKING POT AND AMP VALUES FOR SHIP #1
      DIMENSION POTAD(30),POTVAL(30),AMPAD(30),AMPVAL(30)
      INTEGER POTAD,AMPAD
      DATA IFLAG/0/,IFLAG1/0/
      DATA N1/24/
      READ(5,100) (POTAD(I),POTVAL(I),I=1,N1)
  100 FORMAT(A4,F10.4)
      DO 10 I=1,N1
   10 CALL SETPOT(POTAD(I),POTVAL(I))
      WRITE(6,101) (POTAD(I),POTVAL(I),I=1,N1)
  101 FORMAT(A4,F10.4)
      READ(5,102) (AMPAD(I),I=1,29)
  102 FORMAT(A4)
      CALL RESET(1000)
      DO 12 I=1,29
   12 CALL SCAN(AMPAD(I),AMPVAL(I))
      WRITE(6,103) (AMPAD(I),AMPVAL(I),I=1,29)
  103 FORMAT(A4,F10.6)
      DO 20 I=1,N1
   20 CALL SCAN(POTAD(I),POTVAL(I))
      WRITE(6,200)(POTAD(I),POTVAL(I),I=1,N1)
  200 FORMAT(A4,F10.6)
C WHEN READY
   30 OUTPUT(101) 'READY'
C TRANSFORMATION OF COORDINATES FOR SHIP #1
   11 CALL COMPUTE
  111 CALL ADK(0,U1BAR,1,V1BAR,2,PSIBAR)
      WRITE(6,201) U1BAR,V1BAR,PSIBAR
  201 FORMAT(' ','U1BAR',E14.8,2X,'V1BAR',E14.8,2X,'PSIBAR',
C RESCALING OF PSIBAR
      PSIMAX=0.26
      PSI=PSIMAX*PSIBAR
      A=SIN(PSI)
      B=COS(PSI)
      WRITE(6,106) A,B
  106 FORMAT(' ','A=',E14.8,2X,'B=',E14.8)
      WRITE(6,202) PSI
  202 FORMAT(' ','PSI=',E14.8)
      XO1DOT=U1BAR*B-V1BAR*A
      YO1DOT=U1BAR*A+V1BAR*B
      WRITE(6,107) XO1DOT,YO1DOT
  107 FORMAT(' ','XO1DOT=',E14.8,2X,'YO1DOT=',E14.8)
      CALL DAC(1,XO1DOT,2,YO1DOT)
C MANUAL DIGITAL SWITCH'O' AND '1'
   15 IF(TEST(1).GT.0) GO TO 16
      CALL HOLD
   17 IF(TEST(1).LT.0) GO TO 17
      CALL COMPUTE
   16 IF(TEST(3).GT.0) GO TO 111
      CALL RESET(1000)
      PAUSE
      GO TO 11
      END
¬LOAD XR,MAP
¬DATA
P000  0.3000
P025  0.2860
P002  0.0803
P033  0.2860
P004  0.0404
P005  0.0052
P006  0.1660
P010  0.2379
P011  0.2383
```

P012	0.4717
P013	0.0250
P015	0.5607
P016	0.1340
P017	0.000
P020	0.0920
P021	0.0097
P022	0.3576
P053	0.0905
P027	0.1750
P055	0.1497
P050	0.0337
P051	0.3000
P056	0.0092
P057	0.4540
A001	
D001	
A002	
A003	
D003	
A201	
A006	
A005	
D005	
A010	
A014	
A016	
A013	
D013	
A017	
D017	
A022	
A203	
A112	
A060	
A053	
D053	
A206	
A200	
A051	
D051	
A057	
D057	
A202	

COMPUTER PROGRAM IVB

```
*
*
*
*     COORDINATES TRANSFORMATION FOR SHIP NO 2
¬JOB GAL1225
¬ASSIGN 6=NO
¬FORTRAN LS,GO
C   SECTION CHECKING POT AND AMP VALUES FOR SHIP #2
      DIMENSION POTAD(30),POTVAL(30),AMPAD(30),AMPVAL(30)
      INTEGER POTAD,AMPAD
      DATA IFLAG/0/,IFLAG1/0/
      DATA N2/22/
      READ(5,100) (POTAD(I),POTVAL(I),I=1,N2)
  100 FORMAT(A4,F10.4)
      DO 10 I=1,N2
   10 CALL SETPOT(POTAD(I),POTVAL(I))
      WRITE(6,101) (POTAD(I),POTVAL(I),I=1,N2)
  101 FORMAT(A4,F10.4)
      READ(5,102) (AMPAD(I),I=1,27)
  102 FORMAT(A4)
      CALL RESET(1000)
      DO 12 I=1,27
   12 CALL SCAN(AMPAD(I),AMPVAL(I))
      WRITE(6,103) (AMPAD(I),AMPVAL(I),I=1,27)
  103 FORMAT(A4,F10.6)
      DO 20 I=1,N2
   20 CALL SCAN(POTAD(I),POTVAL(I))
      WRITE(6,200)(POTAD(I),POTVAL(I),I=1,N2)
  200 FORMAT(A4,F10.6)
C WHEN READY
   30 OUTPUT(101) 'READY'
C TRANSFORMATION OF COORDINATES FOR SHIP #2
   11 CALL COMPUTE
  112 CALL ADK(4,U2BAR,5,V2BAR,6,PS2BAR)
C RESCALING OF PS2BAR
      PS2MAX=0.26
      PS2=PS2MAX*PS2BAR
      A2=SIN(PS2)
      B2=COS(PS2)
      XO2DOT=U2BAR*B2-V2BAR*A2
      YO2DOT=U2BAR*A2+V2BAR*B2
      CALL DAC(5,YO2DOT,6,XO2DOT)
C MANUAL DIGITAL SWITCH  '2' AND '3'
   18 IF(TEST(2).GT.0) GO TO 19
      CALL HOLD
   21 IF(TEST(2).LT.0) GO TO 21
      CALL COMPUTE
   19 IF(TEST(4).GT.0) GO TO 112
      CALL RESET(1000)
      PAUSE
      GO TO 11
      END
¬LOAD XR,MAP
¬DATA
P024  0.3000
P054  0.2860
P026  0.0803
P001  0.1750
P030  0.0404
P045  0.0920
P031  0.0052
P023  0.0905
P034  0.1660
P003  0.2860
P046  0.4717
P032  0.2379
P035  0.2383
P047  0.1497
P036  0.0097
P037  0.0250
P041  0.1340
```

P042	0.0000
P043	0.5607
P044	0.3576
P007	0.0337
P014	0.0092
A035	
D035	
A026	
A027	
D027	
A044	
A034	
A033	
D033	
A030	
A036	
A041	
D041	
A043	
D043	
A042	
A104	
A052	
A007	
D007	
A205	
A204	
A065	
D065	
A214	
A061	
D061	

COMPUTER PROGRAM VA

```
*
*
*
*     PHASE I.INTERACTION FORCE AND MOMENT ARE APPLIED TO THE
*     LEADING SHIP(SHIP MODEL NO 2)
¬JOB GAL1225
¬FORTRAN LS,GO
       REAL NMAX,NDIM,NSCAL
       REAL NBAR,N,NBAR1
       DIMENSION Y(30,30),N(30,30)
       DIMENSION POTAD(70),POTVAL(70),AMPAD(70),AMPVAL(70)
       INTEGER POTAD,AMPAD
       DATA IFLAG/0/,IFLAG1/0/
       DATA NO/48/
C STORAGE OF NONDIMENSIONAL ARRAY FOR NAND Y
       DO 10 J=1,25
    10 READ(5,100) (Y(J,I),I=1,6)
   100 FORMAT(6E11.4)
       DO 12 J=1,25
    12 READ(5,100) (N(J,I),I=1,6)
X      WRITE(6,200)
   200 FORMAT(' ','THIS IS Y(J,I)',//)
       DO 11J=1,25
X      WRITE (6,201) (Y(J,I),I=1,6)
   201 FORMAT(' ',10X,6(E11.4,2X),//)
    11 CONTINUE
X      WRITE(6,300)
   300 FORMAT(' ','THIS IS N(J,I)',//)
       DO 13 J=1,25
X      WRITE(6,301) (N(J,I),I=1,6)
   301 FORMAT(' ',10X,6(E11.4,2X),//)
    13 CONTINUE
C  SECTION CHECKING POT AND AMP VALUES FOR SHIP #1 AND #2
       READ(5,1005) (POTAD(I),POTVAL(I),I=1,NO)
  1005 FORMAT(A4,F10.4)
       DO 105 I=1,NO
   105 CALL SETPOT(POTAD(I),POTVAL(I))
X      WRITE(6,1015) (POTAD(I),POTVAL(I),I=1,NO)
  1015 FORMAT(A4,F10.4)
       READ(5,1025) (AMPAD(I),I=1,66)
  1025 FORMAT(A4)
       CALL RESET(1000)
       DO 125 I=1,66
   125 CALL SCAN(AMPAD(I),AMPVAL(I))
X      WRITE(6,103) (AMPAD(I),AMPVAL(I),I=1,66)
   103 FORMAT(A4,F10.6)
       DO 20 I=1,NO
    20 CALL SCAN(POTAD(I),POTVAL(I))
X      WRITE(6,2005)(POTAD(I),POTVAL(I),I=1,NO)
  2005 FORMAT(A4,F10.6)
C WHEN READY
    30 OUTPUT(101) 'READY'
C TRANSFORMATION OF COORDINATES FOR SHIP #1 AND #2
   115 CALL COMPUTE
   111 CALL ADK(0,U1BAR,1,V1BAR,2,PSIBAR,4,U2BAR,5,V2BAR,6,PS
      6R,3,ALPBAR)
C RESCALING OF PSIBAR AND PS2BAR
       PSIMAX=0.26
       PS2MAX=0.26
       PSI=PSIMAX*PSIBAR
       A=SIN(PSI)
       B=COS(PSI)
       XO1DOT=U1BAR*B-V1BAR*A
       YO1DOT=U1BAR*A+V1BAR*B
       PS2=PS2MAX*PS2BAR
       A2=SIN(PS2)
       B2=COS(PS2)
       XO2DOT=U2BAR*B2-V2BAR*A2
       YO2DOT=U2BAR*A2+V2BAR*B2
C INTERPOLATION IN 2-DIM. ARRAY.PASS BETBAR AND ALPBAR
C REMEMBER BETBAR=1.0 CORRESPONDS BETA=100.0 FEET***
```

```
C ALPBAR=1.0 CORRESPONDS ALPHA=550.0 FEET
C ALSO BETBAR AND ALPBAR ARE PAST IN COMPUTER UNITS
X     WRITE(6,401)
  401 FORMAT(' ',10X,'THIS IS ALPBAR-BETBAR',//)
X     WRITE(6,402) ALPBAR,BETBAR
  402 FORMAT(' ',10X,2F11.6)
C RESCALING OF ALPHABAR=ALPBAR AND BETABAR=BETBAR
      ALPHA=550.0*ALPBAR
X     WRITE(6,403)
  403 FORMAT(' ',10X,'THIS IS ALPHA',//)
X     WRITE(6,501)ALPHA
      BETA=100.0*BETBAR
X     WRITE(6,404)
  404 FORMAT(' ',10X,'THIS IS BETA',//)
X     WRITE(6,501)BETA
      IF(BETA.LT.50.0) OUTPUT(101) BETA;NSCAL=0.0;YSCAL=0.0;
      IF(BETA.GT.100.0)OUTPUT(101)BETA;NSCAL=0.0;YSCAL=0.0;G
      IF(ALPHA.GT.550.0)OUTPUT(101)ALPHA;NSCAL=0.0;YSCAL=0.0
      IF(ALPHA.LT.-550.0)OUTPUT(101)ALPHA;NSCAL=0.0;YSCAL=0.
C SEARCH FOR INDETIFICATION OF ARRAY ELEMENT
C FIND CORRESPONDED Y AND N -LINEAR INTERPOLATION IN 2-DIMEN
      IB1=BETA/10.0
      IB=IB1-4
      BETA1=IB1*10
      WTB=(BETA-BETA1)/10.0
      IF(ALPHA.LT.0.0) GO TO 1
      IF(ALPHA.GT.0.0) GO TO 2
C ALPHA =0
      IA=13
      WTA=0.0
      GO TO 3
C ALPHA LESS THAN ZERO
    1 IA1=-ALPHA/50.0
      ALPHA1=-IA1*50
      WTA=-(ALPHA-ALPHA1)/50.0
      IA=13-IA1
      GO TO 3
C ALPHA GREATER THAN ZERO
    2 IA1=ALPHA/50.0
      IA=13+IA1
      ALPHA1=IA1*50
      WTA=(ALPHA-ALPHA1)/50.0
    3 IB2=IB+1
      IF(IB.EQ.6) IB2=6
      IA2=IA+1
      IF(IA.EQ.25) IA2=25
X     WRITE(6,101) IB1,IB,IB2,IA1
  101 FORMAT(' ',10X,'IB1=',I3,5X,'IB=',I3,5X,'IB2=',I3,5X,'
X     WRITE(6,102) IA,IA2
  102 FORMAT(' ',10X,'IA=',I3,5X,'IA2=',I3,//)
X     WRITE(6,202) BETA1,WTB,ALPHA1
  202 FORMAT(' ','BETA1',E14.8,2X,'WTB',E14.8,2X,'ALPHA1',E1
X     WRITE(6,203) WTA
  203 FORMAT(' ','WTA=',E14.8,//)
      IF(ALPHA.LT.0.0) IA2=IA-1
      IF(IA.EQ.1) IA2=1
      IF(WTA.EQ.0.0)IA2=IA
      IF(WTB.EQ.0.0) IB2=IB
      NBAR1=N(IA,IB2)
X     WRITE(6,602)
  602 FORMAT(' ','THIS IS NBAR1',//)
X     WRITE(6,502) NBAR1,IA,IB2
      NBAR=N(IA,IB)
X     WRITE(6,603)
  603 FORMAT(' ','THIS IS NBAR',//)
X     WRITE(6,502) NBAR,IA,IB
      BARN1=(NBAR1-NBAR)*WTB+NBAR
X     WRITE(6,604)
  604 FORMAT(' ','THIS IS BARN1',//)
X     WRITE(6,501) BARN1
      NBAR1=N(IA2,IB2)
X     WRITE(6,605)
```

```
  6C5 FCRMAT(' ','THIS IS NBAR1',//)
X       WRITE(6,502) NBAR1,IA2,IB2
        NBAR=N(IA2,IB)
X       WRITE(6,606)
  606 FORMAT(' ','THIS IS NBAR',//)
X       WRITE(6,502) NBAR,IA2,IB
        BARN2=(NBAR1-NBAR)*WTB+NBAR
X       WRITE(6,607)
  607 FORMAT(' ','THIS IS BARN2',//)
X       WRITE(6,501) BARN2
        NBAR=(BARN2-BARN1)*WTA+BARN1
X       WRITE(6,500)
  50C FORMAT(' ','THIS IS FINAL NBAR',//)
X       WRITE(6,501) NBAR
  501 FCRMAT(' ',10X,E14.8,//)
        YBAR1=Y(IA,IB2)
X       WRITE(6,608)
  608 FORMAT(' ','THIS IS YBAR1',//)
X       WRITE(6,502) YBAR1,IA,IB2
        YBAR=Y(IA,IB)
X       WRITE(6,609)
  609 FCRMAT(' ','THIS IS YBAR',//)
X       WRITE(6,502) YBAR,IA,IB
        BARY1=(YBAR1-YBAR)*WTB+YBAR
X       WRITE(6,610)
  61C FORMAT(' ','THIS IS BARY1',//)
X       WRITE(6,601)BARY1
        YBAR1=Y(IA2,IB2)
X       WRITE(6,611)
  611 FORMAT(' ','THIS IS YBAR1',//)
X       WRITE(6,502) YBAR1,IA2,IB2
        YBAR=Y(IA2,IB)
X       WRITE(6,612)
  612 FCRMAT(' ','THIS IS YBAR',//)
X       WRITE(6,502) YBAR,IA2,IB
        BARY2=(YBAR1-YBAR)*WTB+YBAR
X       WRITE(6,613)
  613 FORMAT(' ','THIS IS BARY2',//)
X       WRITE(6,601) BARY2
        YBAR=(BARY2-BARY1)*WTA+BARY1
X       WRITE(6,600)
  6CC FORMAT(' ','THIS IS FINAL YBAR',//)
X       WRITE(6,601) YBAR
  601 FCRMAT(' ',10X,E14.8,//)
  5C2 FORMAT(' ',10X,E14.8,5X,'ROW=',I3,1X,'COL=',I3)
C REMEMBER SIMULATION IS DONE IN COMPUTER UNITS SC NO NEED T
C**** DIVIDE BY 100.0 SINCE SUBR. DAC CCNVERTS BY ITSELF IN
C MAGNITUDE SCALING OF N
        NMAX=4.195E+07
        NDIM=NBAR*(9.428E+10)
        NSCAL=NDIM/NMAX
C MAGNITUDE SCALING OF Y
        YMAX=1.608E+05
        YDIM=YBAR*(17.875+07)
        YSCAL=YDIM/YMAX
X       WRITE(6,900) NSCAL,YSCAL
  900 FORMAT(' ','NSCAL=',E14.6,5X,'YSCAL=',E14.6,//)
X       WRITE(6,901) NDIM,YDIM
  901 FORMAT(' ','NDIM=',E14.6,5X,'YDIM=',E14.6,//)
X       WRITE(6,5001) X01DOT,Y01DOT
 5CC1 FORMAT(' ','X01DOT=',E14.6,'Y01DCT=',E14.6,//)
X       WRITE(6,5000) X02DOT,Y02DOT
 5000 FORMAT(' ','X02DOT=',E14.6,'Y02DOT=',E14.6,//)
C TRUNK LINES T426(7) FOR A076,T427(8) FCR A072,T422(3), FOR
C***T423(4) FOR A207
  804 CALL DAC(1,X01DOT,2,Y01DOT,5,Y02DOT,6,X02DCT,3,NSCAL,4
C MANUAL DIGITAL SWITCH'0' AND '1'
   15 IF(TEST(1).GT.0) GC TO 16
        CALL HOLD
   17 IF(TEST(1).LT.0) GC TO 17
        CALL COMPUTE
   16 IF(TEST(3).GT.0) GC TO 111
```

```
      CALL RESET(1000)
      PAUSE
      GO TO 115
      END
¬LOAD XR,MAP
¬DATA
*
*
*
*                               THIS IS Y ARRAY
*
*
*
-0.1400E-03-0.1263E-03-0.1160E-03-0.1058E-03-0.9753E-04-0.90
-0.2400E-03-0.2112E-03-0.1897E-03-0.1681E-03-0.1508E-03-0.13
-0.3200E-03-0.2762E-03-0.2433E-03-0.2104E-03-0.1841E-03-0.16
-0.3800E-03-0.3225E-03-0.2793E-03-0.2362E-03-0.2016E-03-0.17
-0.4000E-03-0.3337E-03-0.2840E-03-0.2342E-03-0.1945E-03-0.15
-0.3500E-03-0.2870E-03-0.2397E-03-0.1925E-03-0.1547E-03-0.12
-0.2600E-03-0.2079E-03-0.1689E-03-0.1299E-03-0.9863E-04-0.70
-0.1300E-03-0.9384E-04-0.6671E-04-0.3959E-04-0.1789E-04 0.20
 0.4000E-04 0.5507E-04 0.6637E-04 0.7767E-04 0.8671E-04 0.95
 0.2700E-03 0.2508E-03 0.2364E-03 0.2221E-03 0.2105E-03 0.20
 0.5000E-03 0.4507E-03 0.4137E-03 0.3767E-03 0.3471E-03 0.32
 0.7000E-03 0.6225E-03 0.5643E-03 0.5062E-03 0.4596E-03 0.41
 0.8500E-03 0.7500E-03 0.6750E-03 0.6000E-03 0.5400E-03 0.48
 0.9000E-03 0.7844E-03 0.6977E-03 0.6110E-03 0.5416E-03 0.47
 0.8200E-03 0.7159E-03 0.6378E-03 0.5597E-03 0.4973E-03 0.44
 0.6250E-03 0.5579E-03 0.5075E-03 0.4572E-03 0.4169E-03 0.38
 0.4500E-03 0.4089E-03 0.3781E-03 0.3473E-03 0.3226E-03 0.30
 0.3000E-03 0.2781E-03 0.2616E-03 0.2452E-03 0.2321E-03 0.22
 0.1700E-03 0.1673E-03 0.1652E-03 0.1632E-03 0.1615E-03 0.16
 0.6000E-04 0.6822E-04 0.7438E-04 0.8055E-04 0.8548E-04 0.90
-0.2000E-04-0.3562E-05 0.8767E-05 0.2110E-04 0.3096E-04 0.40
-0.5000E-04-0.3493E-04-0.2363E-04-0.1233E-04-0.3288E-05 0.50
-0.6000E-04-0.4904E-04-0.4082E-04-0.3260E-04-0.2603E-04-0.20
-0.5000E-04-0.4699E-04-0.4473E-04-0.4247E-04-0.4065E-04-0.39
-0.1000E-04-0.2096E-04-0.2918E-04-0.3740E-04-0.4397E-04-0.50
*
*
*
*                               THIS IS N ARRAY
*
*
*
 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.60
 0.1100E-03 0.1036E-03 0.9786E-04 0.9280E-04 0.8890E-04 0.85
 0.1390E-03 0.1278E-03 0.1176E-03 0.1087E-03 0.1019E-03 0.95
 0.1530E-03 0.1349E-03 0.1186E-03 0.1042E-03 0.9308E-04 0.82
 0.1400E-03 0.1197E-03 0.1012E-03 0.8497E-04 0.7249E-04 0.60
 0.7000E-04 0.5728E-04 0.4572E-04 0.3561E-04 0.2780E-04 0.20
-0.5000E-04-0.4618E-04-0.4272E-04-0.3968E-04-0.3734E-04-0.35
-0.1750E-03-0.1536E-03-0.1342E-03-0.1172E-03-0.1041E-03-0.91
-0.3000E-03-0.2598E-03-0.2238E-03-0.1913E-03-0.1667E-03-0.14
-0.4100E-03-0.3528E-03-0.3008E-03-0.2552E-03-0.2201E-03-0.18
-0.4420E-03-0.3880E-03-0.3294E-03-0.2824E-03-0.2462E-03-0.21
-0.4350E-03-0.3785E-03-0.3272E-03-0.2823E-03-0.2476E-03-0.21
-0.3740E-03-0.3300E-03-0.2900E-03-0.2550E-03-0.2280E-03-0.20
-0.2800E-03-0.2520E-03-0.2266E-03-0.2043E-03-0.1872E-03-0.17
-0.1500E-03-0.1373E-03-0.1257E-03-0.1156E-03-0.1078E-03-0.10
-0.4500E-03-0.4373E-04-0.4257E-04-0.4156E-04-0.4078E-04-0.40
 0.4200E-04 0.3640E-04 0.3132E-04 0.2687E-04 0.2343E-04 0.20
 0.1100E-03 0.9728E-04 0.8572E-04 0.7561E-04 0.6780E-04 0.60
 0.1400E-03 0.1247E-03 0.1109E-03 0.9873E-04 0.8936E-04 0.80
 0.1320E-03 0.1193E-03 0.1077E-03 0.9761E-04 0.8980E-04 0.82
 0.1200E-03 0.1060E-03 0.9329E-04 0.8217E-04 0.7358E-04 0.65
 0.1020E-03 0.8750E-04 0.7432E-04 0.6279E-04 0.5390E-04 0.45
 0.7500E-04 0.6355E-04 0.5315E-04 0.4405E-04 0.3702E-04 0.30
 0.4500E-04 0.3864E-04 0.3286E-04 0.2780E-04 0.2390E-04 0.20
 0.9000E-05 0.1053E-04 0.1191E-04 0.1313E-04 0.1406E-04 0.15
P000  0.1511
P040  0.1600
```

P052	0.1600
P025	0.2860
P002	0.0803
P033	0.2860
P004	0.0404
P005	0.0052
P006	0.1660
P010	0.2379
P011	0.2383
P012	0.4717
P013	0.0250
P015	0.5607
P016	0.1340
P020	0.0920
P021	0.0097
P022	0.3576
P053	0.0905
P027	0.1750
P055	0.1497
P050	0.0337
P051	0.4380
P056	0.0092
P057	0.9540
P024	0.1581
P054	0.2860
P026	0.0803
P001	0.1750
P030	0.0404
P045	0.0920
P031	0.0052
P023	0.0905
P034	0.1660
P003	0.2860
P046	0.4717
P032	0.2379
P035	0.2383
P047	0.1497
P036	0.0097
P037	0.0250
P041	0.1340
P043	0.5607
P044	0.3576
P007	0.0337
P014	0.0092
P042	0.1511
P017	0.1581
A001	
D001	
A002	
A003	
D003	
A201	
A006	
A005	
D005	
A010	
A014	
A016	
A013	
D013	
A017	
D017	
A022	
A203	
A112	
A060	
A053	
D053	
A206	
A200	
A051	
D051	

A057
D057
A202
A035
D035
A026
A027
D027
A044
A034
A033
D033
A030
A036
A041
D041
A043
D043
A042
A104
A052
A007
D007
A205
A204
A065
D065
A214
A061
D061
A211
A066
A056
A024
A216
A213
A207
A064
A210
A212

COMPUTER PROGRAM VB

```
*
*
*
*     PHASE I.INTERACTION FORCE AND MOMENT ARE APPLIED TO THE
*    LEADING SHIP(SHIP MODEL NO 1)
¬JOB GAL1225
¬FORTRAN LS,GC
      REAL NMAX,NDIM,NSCAL
      REAL NBAR,N,NBAR1
      DIMENSION Y(30,30),N(30,30)
      DIMENSION POTAD(70),POTVAL(70),AMPAD(70),AMPVAL(70)
      INTEGER POTAD,AMPAD
      DATA IFLAG/0/,IFLAG1/0/
      DATA NO/48/
C STORAGE OF NONDIMENSIONAL ARRAY FOR NAND Y
      DO 10 J=1,25
   10 READ(5,100) (Y(J,I),I=1,6)
  100 FORMAT(6E11.4)
      DO 12 J=1,25
   12 READ(5,100) (N(J,I),I=1,6)
C MANUAL SWITCH '2' UP FOR BYPASS SETPOTAND SCAN
      IF(TEST(2).GT.0) CALL RESET(1000);CALL COMPUTE;GO TO 1
X     WRITE(6,200)
  200 FORMAT(' ','THIS IS Y(J,I)',//)
      DO 11J=1,25
X     WRITE (6,201) (Y(J,I),I=1,6)
  201 FORMAT(' ',10X,6(E11.4,2X),//)
   11 CONTINUE
X     WRITE(6,300)
  300 FORMAT(' ','THIS IS N(J,I)',//)
      DO 13 J=1,25
X     WRITE(6,301) (N(J,I),I=1,6)
  301 FORMAT(' ',10X,6(E11.4,2X),//)
   13 CONTINUE
C   SECTION CHECKING POT AND AMP VALUES FOR SHIP #1 AND #2
      READ(5,1005) (POTAD(I),POTVAL(I),I=1,NO)
 1005 FORMAT(A4,F10.4)
      DO 105 I=1,NO
  105 CALL SETPOT(POTAD(I),POTVAL(I))
X     WRITE(6,1015) (POTAD(I),POTVAL(I),I=1,NO)
 1015 FORMAT(A4,F10.4)
      READ(5,1025) (AMPAD(I),I=1,66)
 1025 FORMAT(A4)
      CALL RESET(1000)
      DO 125 I=1,66
  125 CALL SCAN(AMPAD(I),AMPVAL(I))
X     WRITE(6,103) (AMPAD(I),AMPVAL(I),I=1,66)
  103 FORMAT(A4,F10.6)
      DO 20 I=1,NO
   20 CALL SCAN(POTAD(I),POTVAL(I))
X     WRITE(6,2005)(POTAD(I),POTVAL(I),I=1,NO)
 2005 FORMAT(A4,F10.6)
C WHEN READY
   30 OUTPUT(101) 'READY'
C TRANSFORMATION OF COORDINATES FOR SHIP #1 AND #2
  115 CALL COMPUTE
  111 CALL ADK(0,U1BAR,1,V1BAR,2,PSIBAR,4,U2BAR,5,V2BAR,6,PS
     6R,3,ALPBAR)
C RESCALING OF PSIBAR AND PS2BAR
      PSIMAX=0.26
      PS2MAX=0.26
      PSI=PSIMAX*PSIBAR
      A=SIN(PSI)
      B=COS(PSI)
      XC1DOT=U1BAR*B-V1BAR*A
      YO1DOT=U1BAR*A+V1BAR*B
      PS2=PS2MAX*PS2BAR
      A2=SIN(PS2)
      B2=COS(PS2)
      XC2DOT=U2BAR*B2-V2BAR*A2
      YC2DOT=U2BAR*A2+V2BAR*B2
```

```
C INTERPOLATICN IN 2-DIM. ARRAY.PASS BETBAR AND ALPBAR
C REMEMBER BETBAR=1.0 CCRRESPONDS BETA=100.0 FEET***
C ALPBAR=1.0 CCRRESPONDS ALPHA=550.0 FEET
C ALSC BETBAR AND ALPBAR ARE PAST IN COMPUTER UNITS
X       WRITE(6,401)
  401 FCRMAT(' ',10X,'THIS IS ALPBAR-BETBAR',//)
X       WRITE(6,402) ALPBAR,BETBAR
  402 FCRMAT(' ',10X,2F11.6)
C RESCALING OF ALPHABAR=ALPBAR AND BETABAR=BETBAR
        ALPHA=550.0*ALPBAR
X       WRITE(6,403)
  403 FORMAT(' ',10X,'THIS IS ALPHA',//)
X       WRITE(6,501)ALPHA
        BETA=100.0*BETBAR
X       WRITE(6,404)
  404 FCRMAT(' ',10X,'THIS IS BETA',//)
X       WRITE(6,501)BETA
        IF(BETA.LT.50.0) OUTPUT(101) BETA;NSCAL=0.0;YSCAL=0.0;
        IF(BETA.GT.100.0)OUTPUT(101)BETA;NSCAL=0.0;YSCAL=0.0;G
        IF(ALPHA.GT.550.0)OUTPUT(101)ALPHA;NSCAL=C.C;YSCAL=0.0
        IF(ALPHA.LT.-550.0)OUTPUT(101)ALPHA;NSCAL=0.0;YSCAL=0.
C SEARCH FCR INDETIFICATICN CF ARRAY ELEMENT
C FIND CORRESPONDED Y AND N -LINEAR INTERPOLATICN IN 2-DIMEN
        IB1=BETA/10.0
        IB=IB1-4
        BETA1=IB1*10
        WTB=(BETA-BETA1)/10.0
        IF(ALPHA.LT.0.0) GO TO 1
        IF(ALPHA.GT.0.0) GO TO 2
C ALPHA =0
        IA=13
        WTA=0.0
        GO TO 3
C ALPHA LESS THAN ZERO
    1 IA1=-ALPHA/50.0
        ALPHA1=-IA1*50
        WTA=-(ALPHA-ALPHA1)/50.0
        IA=13-IA1
        GC TO 3
C ALPHA GREATER THAN ZERO
    2 IA1=ALPHA/50.0
        IA=13+IA1
        ALPHA1=IA1*50
        WTA=(ALPHA-ALPHA1)/50.0
    3 IB2=IB+1
        IF(IB.EQ.6) IB2=6
        IA2=IA+1
        IF(IA.EQ.25) IA2=25
X       WRITE(6,101) IB1,IB,IB2,IA1
  101 FCRMAT(' ',10X,'IB1=',I3,5X,'IB=',I3,5X,'IB2=',I3,5X,'
X       WRITE(6,102) IA,IA2
  102 FCRMAT(' ',10X,'IA=',I3,5X,'IA2=',I3,//)
X       WRITE(6,202) BETA1,WTB,ALPHA1
  202 FCRMAT(' ','BETA1',E14.8,2X,'WTB',E14.8,2X,'ALPHA1',E1
X       WRITE(6,203) WTA
  203 FORMAT(' ','WTA=',E14.8,//)
        IF(ALPHA.LT.0.0) IA2=IA-1
        IF(IA.EQ.1) IA2=1
        IF(WTA.EQ.0.0)IA2=IA
        IF(WTB.EQ.0.0) IB2=IB
        NBAR1=N(IA,IB2)
X       WRITE(6,602)
  602 FCRMAT(' ','THIS IS NBAR1',//)
X       WRITE(6,502) NBAR1,IA,IB2
        NBAR=N(IA,IB)
X       WRITE(6,603)
  603 FCRMAT(' ','THIS IS NBAR',//)
X       WRITE(6,502) NBAR,IA,IB
        BARN1=(NBAR1-NBAR)*WTB+NBAR
X       WRITE(6,604)
  604 FCRMAT(' ','THIS IS BARN1',//)
X       WRITE(6,501) BARN1
```

```
      NBAR1=N(IA2,IB2)
X     WRITE(6,605)
  605 FORMAT(' ','THIS IS NBAR1',//)
X     WRITE(6,502) NBAR1,IA2,IB2
      NBAR=N(IA2,IB)
X     WRITE(6,606)
  606 FORMAT(' ','THIS IS NBAR',//)
X     WRITE(6,502) NBAR,IA2,IB
      BARN2=(NBAR1-NBAR)*WTB+NBAR
X     WRITE(6,607)
  607 FORMAT(' ','THIS IS BARN2',//)
X     WRITE(6,501) BARN2
      NBAR=(BARN2-BARN1)*WTA+BARN1
X     WRITE(6,500)
  500 FORMAT(' ','THIS IS FINAL NBAR',//)
X     WRITE(6,501) NBAR
  501 FORMAT(' ',10X,E14.8,//)
      YBAR1=Y(IA,IB2)
X     WRITE(6,608)
  608 FORMAT(' ','THIS IS YBAR1',//)
X     WRITE(6,502) YBAR1,IA,IB2
      YBAR=Y(IA,IB)
X     WRITE(6,609)
  609 FORMAT(' ','THIS IS YBAR',//)
X     WRITE(6,502) YBAR,IA,IB
      BARY1=(YBAR1-YBAR)*WTB+YBAR
X     WRITE(6,610)
  610 FORMAT(' ','THIS IS BARY1',//)
X     WRITE(6,601)BARY1
      YBAR1=Y(IA2,IB2)
X     WRITE(6,611)
  611 FORMAT(' ','THIS IS YBAR1',//)
X     WRITE(6,502) YBAR1,IA2,IB2
      YBAR=Y(IA2,IB)
X     WRITE(6,612)
  612 FORMAT(' ','THIS IS YBAR',//)
X     WRITE(6,502) YBAR,IA2,IB
      BARY2=(YBAR1-YBAR)*WTB+YBAR
X     WRITE(6,613)
  613 FORMAT(' ','THIS IS BARY2',//)
X     WRITE(6,601) BARY2
      YBAR=(BARY2-BARY1)*WTA+BARY1
X     WRITE(6,600)
  600 FORMAT(' ','THIS IS FINAL YBAR',//)
X     WRITE(6,601) YBAR
  601 FORMAT(' ',10X,E14.8,//)
  502 FORMAT(' ',10X,E14.8,5X,'ROW=',I3,1X,'COL=',I3)
C REMEMBER SIMULATION IS DONE IN COMPUTER UNITS SO NO NEED T
C**** DIVIDE BY 100.0 SINCE SUBR. DAC CONVERTS BY ITSELF IN
C MAGNITUDE SCALING OF N
      NMAX=4.195E+07
      NDIM=NBAR*(9.428E+10)
      NSCAL=NDIM/NMAX
C MAGNITUDE SCALING OF Y
      YMAX=1.608E+05
      YDIM=YBAR*(17.87E+07)
      YSCAL=YDIM/YMAX
  804 CALL DAC(1,X01DOT,2,Y01DOT,5,Y02DOT,6,X02DOT,7,NSCAL,8
C MANUAL DIGITAL SWITCH'0' AND '1'
   15 IF(TEST(1).GT.0) GO TO 16
      CALL HOLD
   17 IF(TEST(1).LT.0) GO TO 17
      CALL COMPUTE
   16 IF(TEST(3).GT.0) GO TO 111
      CALL RESET(1000)
      PAUSE
      GO TO 115
      END
¬LOAD XR,MAP
¬DATA
*
*
```

```
*
*                          THIS IS Y ARRAY
*
*
*
-0.1400E-03-0.1263E-03-0.1160E-03-0.1058E-03-0.9753E-04-0.90
-0.2400E-03-0.2112E-03-0.1897E-03-0.1681E-03-0.1508E-03-0.13
-0.3200E-03-0.2762E-03-0.2433E-03-0.2104E-03-0.1841E-03-0.16
-0.3800E-03-0.3225E-03-0.2793E-03-0.2362E-03-0.2016E-03-0.17
-0.4000E-03-0.3337E-03-0.2840E-03-0.2342E-03-0.1945E-03-0.15
-0.3500E-03-0.2870E-03-0.2397E-03-0.1925E-03-0.1547E-03-0.12
-0.2600E-03-0.2079E-03-0.1689E-03-0.1299E-03-0.9863E-04-0.70
-0.1300E-03-0.9384E-04-0.6671E-04-0.3959E-04-0.1789E-04 0.20
 0.4000E-04 0.5507E-04 0.6637E-04 0.7767E-04 0.8671E-04 0.95
 0.2700E-03 0.2508E-03 0.2364E-03 0.2221E-03 0.2105E-03 0.20
 0.5000E-03 0.4507E-03 0.4137E-03 0.3767E-03 0.3471E-03 0.32
 0.7000E-03 0.6225E-03 0.5643E-03 0.5062E-03 0.4596E-03 0.41
 0.8500E-03 0.7500E-03 0.6750E-03 0.6000E-03 0.5400E-03 0.48
 0.9000E-03 0.7844E-03 0.6977E-03 0.6110E-03 0.5416E-03 0.47
 0.8200E-03 0.7159E-03 0.6378E-03 0.5597E-03 0.4973E-03 0.44
 0.6250E-03 0.5579E-03 0.5075E-03 0.4572E-03 0.4169E-03 0.38
 0.4500E-03 0.4089E-03 0.3781E-03 0.3473E-03 0.3226E-03 0.30
 0.3000E-03 0.2781E-03 0.2616E-03 0.2452E-03 0.2321E-03 0.22
 0.1700E-03 0.1673E-03 0.1652E-03 0.1632E-03 0.1615E-03 0.16
 0.6000E-04 0.6822E-04 0.7438E-04 0.8055E-04 0.8548E-04 0.90
-0.2000E-04-0.3562E-05 0.8767E-05 0.2110E-04 0.3096E-04 0.40
-0.5000E-04-0.3493E-04-0.2363E-04-0.1233E-04-0.3288E-05 0.50
-0.6000E-04-0.4904E-04-0.4082E-04-0.3260E-04-0.2603E-04-0.20
-0.5000E-04-0.4699E-04-0.4473E-04-0.4247E-04-0.4065E-04-0.39
-0.1000E-04-0.2096E-04-0.2918E-04-0.3740E-04-0.4397E-04-0.50
*
*
*
*                          THIS IS N ARRAY
*
*
*
 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.60
 0.1100E-03 0.1036E-03 0.9786E-04 0.9280E-04 0.8890E-04 0.85
 0.1390E-03 0.1278E-03 0.1176E-03 0.1087E-03 0.1019E-03 0.95
 0.1530E-03 0.1349E-03 0.1186E-03 0.1042E-03 0.9308E-04 0.82
 0.1400E-03 0.1197E-03 0.1012E-03 0.8497E-04 0.7249E-04 0.60
 0.7000E-04 0.5728E-04 0.4572E-04 0.3561E-04 0.2780E-04 0.20
-0.5000E-04-0.4618E-04-0.4272E-04-0.3968E-04-0.3734E-04-0.35
-0.1750E-03-0.1536E-03-0.1342E-03-0.1172E-03-0.1041E-03-0.91
-0.3000E-03-0.2598E-03-0.2238E-03-0.1913E-03-0.1667E-03-0.14
-0.4100E-03-0.3528E-03-0.3008E-03-0.2552E-03-0.2201E-03-0.18
-0.4420E-03-0.3880E-03-0.3294E-03-0.2824E-03-0.2462E-03-0.21
-0.4350E-03-0.3785E-03-0.3272E-03-0.2823E-03-0.2476E-03-0.21
-0.3740E-03-0.3300E-03-0.2900E-03-0.2550E-03-0.2280E-03-0.20
-0.2800E-03-0.2520E-03-0.2266E-03-0.2043E-03-0.1872E-03-0.17
-0.1500E-03-0.1373E-03-0.1257E-03-0.1156E-03-0.1078E-03-0.10
-0.4500E-03-0.4373E-04-0.4257E-04-0.4156E-04-0.4078E-04-0.40
 0.4200E-04 0.3640E-04 0.3132E-04 0.2687E-04 0.2343E-04 0.20
 0.1100E-03 0.9728E-04 0.8572E-04 0.7561E-04 0.6780E-04 0.60
 0.1400E-03 0.1247E-03 0.1109E-03 0.9873E-04 0.8936E-04 0.80
 0.1320E-03 0.1193E-03 0.1077E-03 0.9761E-04 0.8980E-04 0.82
 0.1200E-03 0.1060E-03 0.9329E-04 0.8217E-04 0.7358E-04 0.65
 0.1020E-03 0.8750E-04 0.7432E-04 0.6279E-04 0.5390E-04 0.45
 0.7500E-04 0.6355E-04 0.5315E-04 0.4405E-04 0.3702E-04 0.30
 0.4500E-04 0.3864E-04 0.3286E-04 0.2780E-04 0.2390E-04 0.20
 0.9000E-05 0.1053E-04 0.1191E-04 0.1313E-04 0.1406E-04 0.15
P000   0.1511
P040   0.1600
P052   0.1600
P025   0.2860
P002   0.0803
P033   0.2860
P004   0.0404
P005   0.0052
P006   0.1660
P010   0.2379
```

P011	0.2383
P012	0.4717
P013	0.0250
P015	0.5607
P016	0.1340
P020	0.0920
P021	0.0097
P022	0.3576
P053	0.0905
P027	0.1750
P055	0.1497
P050	0.0337
P051	0.4380
P056	0.0092
P057	0.9540
P024	0.1581
P054	0.2860
P026	0.0803
P001	0.1750
P030	0.0404
P045	0.0920
P031	0.0052
P023	0.0905
P034	0.1660
P003	0.2860
P046	0.4717
P032	0.2379
P035	0.2383
P047	0.1497
P036	0.0097
P037	0.0250
P041	0.1340
P043	0.5607
P044	0.3576
P007	0.0337
P014	0.0092
P042	0.1511
P017	0.1581
A001	
D001	
A002	
A003	
D003	
A201	
A006	
A005	
D005	
A010	
A014	
A016	
A013	
D013	
A017	
D017	
A022	
A203	
A112	
A060	
A053	
D053	
A206	
A200	
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D051	
A057	
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A202	
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A044
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COMPUTER PROGRAM VI

```
*
*
*
*     PHASE II.INTERACTION FORCE AND MOMENT ARE APPLIED ON
*     BOTH SHIPS
¬JOB GAL1225
¬FORTRAN LS,GO
      REAL NMAX,NDIM,NSCAL,NBSCAL
      REAL NBAR,N,NBAR1
      DIMENSION Y(30,30),N(30,30)
      DIMENSION POTAD(70),POTVAL(70),AMPAD(70),AMPVAL(70)
      INTEGER POTAD,AMPAD
      DATA NO/48/
C STORAGE OF NONDIMENSIONAL ARRAY FOR NAND Y
      DO 10 J=1,25
   10 READ(5,100) (Y(J,I),I=1,6)
  100 FORMAT(6E11.4)
      DO 12 J=1,25
   12 READ(5,100) (N(J,I),I=1,6)
X     WRITE(6,200)
  200 FORMAT(' ','THIS IS Y(J,I)',//)
      DO 11J=1,25
X     WRITE (6,201) (Y(J,I),I=1,6)
  201 FORMAT(' ',10X,6(E11.4,2X),//)
   11 CONTINUE
X     WRITE(6,300)
  300 FORMAT(' ','THIS IS N(J,I)',//)
      DO 13 J=1,25
X     WRITE(6,301) (N(J,I),I=1,6)
  301 FORMAT(' ',10X,6(E11.4,2X),//)
   13 CONTINUE
C  SECTION CHECKING POT AND AMP VALUES FOR SHIP #1 AND #2
      READ(5,1005) (POTAD(I),POTVAL(I),I=1,NO)
 1005 FORMAT(A4,F10.4)
      DO 105 I=1,NO
  105 CALL SETPOT(POTAD(I),POTVAL(I))
X     WRITE(6,1015) (POTAD(I),POTVAL(I),I=1,NO)
 1015 FORMAT(A4,F10.4)
      READ(5,1025) (AMPAD(I),I=1,66)
 1025 FORMAT(A4)
      CALL RESET(1000)
      DO 125 I=1,66
  125 CALL SCAN(AMPAD(I),AMPVAL(I))
X     WRITE(6,103) (AMPAD(I),AMPVAL(I),I=1,66)
  103 FORMAT(A4,F10.6)
      DO 20 I=1,NO
   20 CALL SCAN(POTAD(I),POTVAL(I))
X     WRITE(6,2005)(POTAD(I),POTVAL(I),I=1,NO)
 2005 FORMAT(A4,F10.6)
C WHEN READY
   30 OUTPUT(101) 'READY'
C TRANSFORMATION OF COORDINATES FOR SHIP #1 AND #2
  115 CALL COMPUTE
      IFLAG=0
  111 CALL ADK(0,U1BAR,1,V1BAR,2,PSIBAR,4,U2BAR,5,V2BAR,6,PS
     6R,3,ALPBAR)
C RESCALING OF PSIBAR AND PS2BAR
      PSIMAX=0.26
      PS2MAX=0.26
      PSI=PSIMAX*PSIBAR
      A=SIN(PSI)
      B=COS(PSI)
      XC1DOT=U1BAR*B-V1BAR*A
      YC1DOT=U1BAR*A+V1BAR*B
      PS2=PS2MAX*PS2BAR
      A2=SIN(PS2)
      B2=COS(PS2)
      XO2DOT=U2BAR*B2-V2BAR*A2
      YC2DOT=U2BAR*A2+V2BAR*B2
C INTERPOLATION IN 2-DIM. ARRAY.PASS BETBAR AND ALPBAR
C REMEMBER BETBAR=1.0 CORRESPONDS BETA=100.0 FEET***
```

```
C ALPBAR=1.0 CORRESPONDS ALPHA=550.0 FEET
C ALSO BETBAR AND ALPBAR ARE PAST IN COMPUTER UNITS
X      WRITE(6,401)
  401 FORMAT(' ',10X,'THIS IS ALPBAR-BETBAR',//)
X      WRITE(6,402) ALPBAR,BETBAR
  402 FORMAT(' ',10X,2F11.6)
C RESCALING OF ALPHABAR=ALPBAR AND BETABAR=BETBAR
       ALPHA=550.0*ALPBAR
  555 CONTINUE
X      WRITE(6,403)
  403 FORMAT(' ',10X,'THIS IS ALPHA',//)
X      WRITE(6,501)ALPHA
       BETA=100.0*BETBAR
X      WRITE(6,404)
  404 FORMAT(' ',10X,'THIS IS BETA',//)
X      WRITE(6,501)BETA
       IF(BETA.LT.50.0) OUTPUT(101) BETA;NSCAL=0.0;YSCAL=0.0;
       IF(BETA.GT.100.0)OUTPUT(101)BETA;NSCAL=0.0;YSCAL=0.0;G
       IF(ALPHA.GT.550.0)OUTPUT(101)ALPHA;NSCAL=C.C;YSCAL=C.0
       IF(ALPHA.LT.-550.0)OUTPUT(101)ALPHA;NSCAL=0.0;YSCAL=0.
C SEARCH FOR INDETIFICATION OF ARRAY ELEMENT
C FIND CORRESPONDED Y AND N -LINEAR INTERPOLATION IN 2-DIMEN
       IB1=BETA/10.0
       IB=IB1-4
       BETA1=IB1*10
       WTB=(BETA-BETA1)/10.0
       IF(ALPHA.LT.0.0) GO TO 1
       IF(ALPHA.GT.0.0) GO TO 2
C ALPHA =0
       IA=13
       WTA=0.0
       GO TO 3
C ALPHA LESS THAN ZERO
    1  IA1=-ALPHA/50.0
       ALPHA1=-IA1*50
       WTA=-(ALPHA-ALPHA1)/50.0
       IA=13-IA1
       GO TO 3
C ALPHA GREATER THAN ZERO
    2  IA1=ALPHA/50.0
       IA=13+IA1
       ALPHA1=IA1*50
       WTA=(ALPHA-ALPHA1)/50.0
    3  IB2=IB+1
       IF(IB.EQ.6) IB2=6
       IA2=IA+1
       IF(IA.EQ.25) IA2=25
X      WRITE(6,101) IB1,IB,IB2,IA1
  101 FORMAT(' ',10X,'IB1=',I3,5X,'IB=',I3,5X,'IB2=',I3,5X,'
X      WRITE(6,102) IA,IA2
  102 FORMAT(' ',10X,'IA=',I3,5X,'IA2=',I3,//)
X      WRITE(6,202) BETA1,WTB,ALPHA1
  202 FORMAT(' ','BETA1',E14.8,2X,'WTB',E14.8,2X,'ALPHA1',E1
X      WRITE(6,203) WTA
  203 FORMAT(' ','WTA=',E14.8,//)
       IF(ALPHA.LT.0.0) IA2=IA-1
       IF(IA.EQ.1) IA2=1
       IF(WTA.EQ.0.0)IA2=IA
       IF(WTB.EQ.0.0) IB2=IB
       NBAR1=N(IA,IB2)
X      WRITE(6,602)
  602 FORMAT(' ','THIS IS NBAR1',//)
X      WRITE(6,502) NBAR1,IA,IB2
       NBAR=N(IA,IB)
X      WRITE(6,603)
  603 FORMAT(' ','THIS IS NBAR',//)
X      WRITE(6,502) NBAR,IA,IB
       BARN1=(NBAR1-NBAR)*WTB+NBAR
X      WRITE(6,604)
  604 FORMAT(' ','THIS IS BARN1',//)
X      WRITE(6,501) BARN1
       NBAR1=N(IA2,IB2)
```

```
X       WRITE(6,605)
  605 FORMAT(' ','THIS IS NBAR1',//)
X       WRITE(6,502) NBAR1,IA2,IB2
        NBAR=N(IA2,IB)
X       WRITE(6,606)
  606 FORMAT(' ','THIS IS NBAR',//)
X       WRITE(6,502) NBAR,IA2,IB
        BARN2=(NBAR1-NBAR)*WTB+NBAR
X       WRITE(6,607)
  607 FORMAT(' ','THIS IS BARN2',//)
X       WRITE(6,501) BARN2
        NBAR=(BARN2-BARN1)*WTA+BARN1
X       WRITE(6,500)
  500 FORMAT(' ','THIS IS FINAL NBAR',//)
X       WRITE(6,501) NBAR
  501 FORMAT(' ',10X,E14.8,//)
        YBAR1=Y(IA,IB2)
X       WRITE(6,608)
  608 FORMAT(' ','THIS IS YBAR1',//)
X       WRITE(6,502) YBAR1,IA,IB2
        YBAR=Y(IA,IB)
X       WRITE(6,609)
  609 FORMAT(' ','THIS IS YBAR',//)
X       WRITE(6,502) YBAR,IA,IB
        BARY1=(YBAR1-YBAR)*WTB+YBAR
X       WRITE(6,610)
  610 FORMAT(' ','THIS IS BARY1',//)
X       WRITE(6,601)BARY1
        YBAR1=Y(IA2,IB2)
X       WRITE(6,611)
  611 FORMAT(' ','THIS IS YBAR1',//)
X       WRITE(6,502) YBAR1,IA2,IB2
        YBAR=Y(IA2,IB)
X       WRITE(6,612)
  612 FORMAT(' ','THIS IS YBAR',//)
X       WRITE(6,502) YBAR,IA2,IB
        BARY2=(YBAR1-YBAR)*WTB+YBAR
X       WRITE(6,613)
  613 FORMAT(' ','THIS IS BARY2',//)
X       WRITE(6,601) BARY2
        YBAR=(BARY2-BARY1)*WTA+BARY1
X       WRITE(6,600)
  600 FORMAT(' ','THIS IS FINAL YBAR',//)
X       WRITE(6,601) YBAR
  601 FORMAT(' ',10X,E14.8,//)
  502 FORMAT(' ',10X,E14.8,5X,'ROW=',I3,1X,'COL=',I3)
C REMEMBER SIMULATION IS DONE IN COMPUTER UNITS SO NO NEED T
C**** DIVIDE BY 100.0 SINCE SUBR. DAC CONVERTS BY ITSELF IN
X       WRITE(6,55555) IFLAG
55555 FORMAT(' ',5X,'IFLAG=',I1,//)
C MAGNITUDE SCALING OF N
        NMAX=4.195E+07
        NDIM=NBAR*(9.428E+10)
        IF(IFLAG.EQ.0) NSCAL=NDIM/NMAX
        IF(IFLAG.EQ.1) NBSCAL=NDIM/NMAX
C MAGNITUDE SCALING OF Y
        YMAX=1.608E+05
        YDIM=YBAR*(17.87E+07)
        IF(IFLAG.EQ.0) YSCAL=YDIM/YMAX
        IF(IFLAG.EQ.1) YBSCAL=YDIM/YMAX
X       WRITE(6,901) NDIM,YDIM
  901 FORMAT(' ','NDIM=',E14.6,5X,'YDIM=',E14.6,//)
X       WRITE(6,5001) XO1DOT,YO1DOT
 5001 FORMAT(' ','XO1DOT=',E14.6,'YO1DOT=',E14.6,//)
X       WRITE(6,5000) XO2DOT,YO2DOT
 5000 FORMAT(' ','XO2DOT=',E14.6,'YO2DOT=',E14.6,//)
        IF(IFLAG.EQ.0) IFLAG=1;ALPHA=-ALPHA;GO TO 555
X       WRITE(6,900) NSCAL,YSCAL,NBSCAL,YBSCAL
  900 FORMAT(' ','NSCAL=',E14.6,2X,'YSCAL=',E14.6,2X,'NBSCAL
     6'YBSCAL=',E14.6,//)
  804 CALL DAC(1,XO1DOT,2,YO1DOT,5,YO2DOT,6,XO2DOT,3,NSCAL,4
     6CAL,8,YBSCAL)
```

```
C MANUAL DIGITAL SWITCH'0' AND '1'
   15 IF(TEST(1).GT.0) GO TO 16
      CALL HOLD
   17 IF(TEST(1).LT.0) GO TO 17
      CALL COMPUTE
   16 IF(TEST(3).GT.0) IFLAG=0;GO TO 111
      CALL RESET(1000)
      PAUSE
      GO TO 115
      END
¬LOAD XR,MAP
¬DATA
*
*
*
*                           THIS IS Y ARRAY
*
*
*
-0.1400E-03-0.1263E-03-0.1160E-03-0.1058E-03-0.9753E-04-0.90
-0.2400E-03-0.2112E-03-0.1897E-03-0.1681E-03-0.1508E-03-0.13
-0.3200E-03-0.2762E-03-0.2433E-03-0.2104E-03-0.1841E-03-0.16
-0.3800E-03-0.3225E-03-0.2793E-03-0.2362E-03-0.2016E-03-0.17
-0.4000E-03-0.3337E-03-0.2840E-03-0.2342E-03-0.1945E-03-0.15
-0.3500E-03-0.2870E-03-0.2397E-03-0.1925E-03-0.1547E-03-0.12
-0.2600E-03-0.2079E-03-0.1689E-03-0.1299E-03-0.9863E-04-0.70
-0.1300E-03-0.9384E-04-0.6671E-04-0.3959E-04-0.1789E-04 0.20
 0.4000E-04 0.5507E-04 0.6637E-04 0.7767E-04 0.8671E-04 0.95
 0.2700E-03 0.2508E-03 0.2364E-03 0.2221E-03 0.2105E-03 0.20
 0.5000E-03 0.4507E-03 0.4137E-03 0.3767E-03 0.3471E-03 0.32
 0.7000E-03 0.6225E-03 0.5643E-03 0.5062E-03 0.4596E-03 0.41
 0.8500E-03 0.7500E-03 0.6750E-03 0.6000E-03 0.5400E-03 0.48
 0.9000E-03 0.7844E-03 0.6977E-03 0.6110E-03 0.5416E-03 0.47
 0.8200E-03 0.7159E-03 0.6378E-03 0.5597E-03 0.4973E-03 0.44
 0.6250E-03 0.5579E-03 0.5075E-03 0.4572E-03 0.4169E-03 0.38
 0.4500E-03 0.4089E-03 0.3781E-03 0.3473E-03 0.3226E-03 0.30
 0.3000E-03 0.2781E-03 0.2616E-03 0.2452E-03 0.2321E-03 0.22
 0.1700E-03 0.1673E-03 0.1652E-03 0.1632E-03 0.1615E-03 0.16
 0.6000E-04 0.6822E-04 0.7438E-04 0.8055E-04 0.8548E-04 0.90
-0.2000E-04-0.3562E-05 0.8767E-05 0.2110E-04 0.3096E-04 0.40
-0.5000E-04-0.3493E-04-0.2363E-04-0.1233E-04-0.3288E-05 0.50
-0.6000E-04-0.4904E-04-0.4082E-04-0.3260E-04-0.2603E-04-0.20
-0.5000E-04-0.4699E-04-0.4473E-04-0.4247E-04-0.4065E-04-0.39
-0.1000E-04-0.2096E-04-0.2918E-04-0.3740E-04-0.4397E-04-0.50
*
*
*
*                           THIS IS N ARRAY
*
*
*
 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.60
 0.1100E-03 0.1036E-03 0.9786E-04 0.9280E-04 0.8890E-04 0.85
 0.1290E-03 0.1278E-03 0.1176E-03 0.1087E-03 0.1019E-03 0.95
 0.1530E-03 0.1349E-03 0.1186E-03 0.1042E-03 0.9308E-04 0.82
 0.1400E-03 0.1197E-03 0.1012E-03 0.8497E-04 0.7249E-04 0.60
 0.7000E-04 0.5728E-04 0.4572E-04 0.3561E-04 0.2780E-04 0.20
-0.5000E-04-0.4618E-04-0.4272E-04-0.3968E-04-0.3734E-04-0.35
-0.1750E-03-0.1536E-03-0.1342E-03-0.1172E-03-0.1041E-03-0.91
-0.3000E-03-0.2598E-03-0.2238E-03-0.1913E-03-0.1667E-03-0.14
-0.4100E-03-0.3528E-03-0.3008E-03-0.2552E-03-0.2201E-03-0.18
-0.4420E-03-0.3880E-03-0.3294E-03-0.2824E-03-0.2462E-03-0.21
-0.4350E-03-0.3785E-03-0.3272E-03-0.2823E-03-0.2476E-03-0.21
-0.3740E-03-0.3300E-03-0.2900E-03-0.2550E-03-0.2280E-03-0.20
-0.2800E-03-0.2520E-03-0.2266E-03-0.2043E-03-0.1872E-03-0.17
-0.1500E-03-0.1373E-03-0.1257E-03-0.1156E-03-0.1078E-03-0.10
-0.4500E-03-0.4373E-04-0.4257E-04-0.4156E-04-0.4078E-04-0.40
 0.4200E-04 0.3640E-04 0.3132E-04 0.2687E-04 0.2343E-04 0.20
 0.1100E-03 0.9728E-04 0.8572E-04 0.7561E-04 0.6780E-04 0.60
 0.1400E-03 0.1247E-03 0.1109E-03 0.9873E-04 0.8936E-04 0.80
 0.1320E-03 0.1193E-03 0.1077E-03 0.9761E-04 0.8980E-04 0.82
 0.1200E-03 0.1060E-03 0.9329E-04 0.8217E-04 0.7358E-04 0.65
```

```
 0.1020E-03 0.8750E-04 0.7432E-04 0.6279E-04 0.5390E-04 0.45
 0.7500E-04 0.6355E-04 0.5315E-04 0.4405E-04 0.3702E-04 0.30
 0.4500E-04 0.3864E-04 0.3286E-04 0.2780E-04 0.2390E-04 0.20
 0.9000E-05 0.1053E-04 0.1191E-04 0.1313E-04 0.1406E-04 0.15
P040   0.1600
P052   0.1600
P000   0.1511
P025   0.2860
P002   0.0803
P033   0.2860
P004   0.0404
P005   0.0052
P006   0.1660
P010   0.2379
P011   0.2383
P012   0.4717
P013   0.0250
P015   0.5607
P016   0.1340
P020   0.0920
P021   0.0097
P022   0.3576
P053   0.0905
P027   0.1750
P055   0.1497
P050   0.0337
P051   0.4380
P056   0.0092
P057   0.9540
P024   0.1581
P054   0.2860
P026   0.0803
P001   0.1750
P030   0.0404
P045   0.0920
P031   0.0052
P023   0.0905
P034   0.1660
P003   0.2860
P046   0.4717
P032   0.2379
P035   0.2383
P047   0.1497
P036   0.0097
P037   0.0250
P041   0.1340
P043   0.5607
P044   0.3576
P007   0.0337
P014   0.0092
P042   0.1511
P017   0.1581
A001
D001
A002
A003
D003
A201
A006
A005
D005
A010
A014
A016
A013
D013
A017
D017
A022
A203
A112
A060
```

A053
D053
A206
A200
A051
D051
A057
D057
A202
A035
D035
A026
A027
D027
A044
A034
A033
D033
A030
A036
A041
D041
A043
D043
A042
A104
A052
A007
D007
A205
A204
A065
D065
A214
A061
D061
A211
A066
A056
A024
A216
A213
A207
A064
A210
A212

COMPUTER PROGRAM VII

```
*
*
*
*     PHASE II.MANUAL CONTROL IS APPLIED
¬JCB GAL1225
¬FORTRAN LS,GC
      REAL NMAX,NDIM,NSCAL,NBSCAL
      REAL NBAR,N,NBAR1
      DIMENSION Y(30,30),N(30,30)
      DIMENSION POTAD(70),POTVAL(70),AMPAD(70),AMPVAL(70)
      INTEGER POTAD,AMPAD
      DATA NO/48/
C STORAGE OF NONDIMENSIONAL ARRAY FOR NAND Y
      DO 10 J=1,25
   10 READ(5,100) (Y(J,I),I=1,6)
  100 FORMAT(6E11.4)
      DO 12 J=1,25
   12 READ(5,100) (N(J,I),I=1,6)
X     WRITE(6,200)
  200 FORMAT(' ','THIS IS Y(J,I)',//)
      DO 11J=1,25
X     WRITE (6,201) (Y(J,I),I=1,6)
  201 FORMAT(' ',10X,6(E11.4,2X),//)
   11 CONTINUE
X     WRITE(6,300)
  300 FORMAT(' ','THIS IS N(J,I)',//)
      DO 13 J=1,25
X     WRITE(6,301) (N(J,I),I=1,6)
  301 FORMAT(' ',10X,6(E11.4,2X),//)
   13 CONTINUE
C  SECTION CHECKING POT AND AMP VALUES FOR SHIP #1 AND #2
      READ(5,1005) (POTAD(I),POTVAL(I),I=1,NO)
 1005 FORMAT(A4,F10.4)
      DO 105 I=1,NO
  105 CALL SETPOT(POTAD(I),PCTVAL(I))
X     WRITE(6,1015) (POTAD(I),POTVAL(I),I=1,NO)
 1015 FORMAT(A4,F10.4)
      READ(5,1025) (AMPAD(I),I=1,66)
 1025 FORMAT(A4)
      CALL RESET(1000)
      DO 125 I=1,66
  125 CALL SCAN(AMPAD(I),AMPVAL(I))
X     WRITE(6,103) (AMPAD(I),AMPVAL(I),I=1,66)
  103 FORMAT(A4,F10.6)
      DO 20 I=1,NO
   20 CALL SCAN(POTAD(I),POTVAL(I))
X     WRITE(6,2005)(POTAD(I),POTVAL(I),I=1,NO)
 2005 FORMAT(A4,F10.6)
C WHEN READY
   30 OUTPUT(101) 'READY'
C TRANSFORMATION OF COORDINATES FOR SHIP #1 AND #2
  115 CALL COMPUTE
      IFLAG=0
  111 CALL ADK(0,U1BAR,1,V1BAR,2,PSIBAR,4,U2BAR,5,V2BAR,6,PS
     6R,3,ALPBAR)
C RESCALING OF PSIBAR AND PS2BAR
      PSIMAX=0.26
      PS2MAX=0.26
      PSI=PSIMAX*PSIBAR
      A=SIN(PSI)
      B=COS(PSI)
      XC1DOT=U1BAR*B-V1BAR*A
      YC1DOT=U1BAR*A+V1BAR*B
      PS2=PS2MAX*PS2BAR
      A2=SIN(PS2)
      B2=COS(PS2)
      XC2DOT=U2BAR*B2-V2BAR*A2
      YC2DOT=U2BAR*A2+V2BAR*B2
C INTERPOLATION IN 2-DIM. ARRAY.PASS BETBAR AND ALPBAR
C REMEMBER BETBAR=1.0 CORRESPONDS BETA=100.0 FEET***
C ALPBAR=1.0 CORRESPONDS ALPHA=550.0 FEET
```

```
C ALSC BETBAR AND ALPBAR ARE PAST IN CCMPUTER UNITS
X      WRITE(6,401)
  401  FCRMAT(' ',10X,'THIS IS ALPBAR-BETBAR',//)
X      WRITE(6,402) ALPBAR,BETBAR
  402  FCPMAT(' ',10X,2F11.6)
C RESCALING OF ALPHABAR=ALPBAR AND BETABAR=BETBAR
       ALPHA=550.0*ALPBAR
  555  CCNTINUE
X      WRITE(6,403)
  403  FCRMAT(' ',10X,'THIS IS ALPHA',//)
X      WRITE(6,501)ALPHA
       BETA=100.0*BETBAR
X      WRITE(6,404)
  404  FCRMAT(' ',10X,'THIS IS BETA',//)
X      WRITE(6,501)BETA
       IF(BETA.LT.50.0) BETA=50.0
       IF(BETA.GT.100.0) BETA=100.0
       IF(ALPHA.GT.550.0) ALPHA=550.0
       IF(ALPHA.LT.-550.0) ALPHA=-550.0
C SEARCH FOR INDETIFICATICN OF ARRAY ELEMENT
C FIND CORRESPONDED Y AND N -LINEAR INTERPOLATICN IN 2-DIMEN
       IB1=BETA/10.0
       IB=IB1-4
       BETA1=IB1*10
       WTB=(BETA-BETA1)/10.0
       IF(ALPHA.LT.0.0) GO TO 1
       IF(ALPHA.GT.0.0) GC TO 2
C ALPHA =0
       IA=13
       WTA=0.0
       GC TO 3
C ALPHA LESS THAN ZERO
    1  IA1=-ALPHA/50.0
       ALPHA1=-IA1*50
       WTA=-(ALPHA-ALPHA1)/50.0
       IA=13-IA1
       GC TO 3
C ALPHA GREATER THAN ZERO
    2  IA1=ALPHA/50.0
       IA=13+IA1
       ALPHA1=IA1*50
       WTA=(ALPHA-ALPHA1)/50.0
    3  IB2=IB+1
       IF(IB.EQ.6) IB2=6
       IA2=IA+1
       IF(IA.EQ.25) IA2=25
X      WRITE(6,101) IB1,IB,IB2,IA1
  101  FCRMAT(' ',10X,'IB1=',I3,5X,'IB=',I3,5X,'IB2=',I3,5X,'
X      WRITE(6,102) IA,IA2
  1C2  FCRMAT(' ',10X,'IA=',I3,5X,'IA2=',I3,//)
X      WRITE(6,202) BETA1,WTB,ALPHA1
  202  FCRMAT(' ','BETA1',E14.8,2X,'WTB',E14.8,2X,'ALPHA1',E1
X      WRITE(6,203) WTA
  203  FCRMAT(' ','WTA=',E14.8,//)
       IF(ALPHA.LT.0.0) IA2=IA-1
       IF(IA.EQ.1) IA2=1
       IF(WTA.EQ.0.0)IA2=IA
       IF(WTB.EQ.0.0) IB2=IB
       NBAR1=N(IA,IB2)
X      WRITE(6,602)
  6C2  FCRMAT(' ','THIS IS NBAR1',//)
X      WRITE(6,502) NBAR1,IA,IB2
       NBAR=N(IA,IB)
X      WRITE(6,603)
  603  FORMAT(' ','THIS IS NBAR',//)
X      WRITE(6,502) NBAR,IA,IB
       BARN1=(NBAR1-NBAR)*WTB+NBAR
X      WRITE(6,604)
  604  FORMAT(' ','THIS IS BARN1',//)
X      WRITE(6,501) BARN1
       NBAR1=N(IA2,IB2)
X      WRITE(6,605)
```

```
  605 FORMAT(' ','THIS IS NBAR1',//)
X      WRITE(6,502) NBAR1,IA2,IB2
       NBAR=N(IA2,IB)
X      WRITE(6,606)
  606 FORMAT(' ','THIS IS NBAR',//)
X      WRITE(6,502) NBAR,IA2,IB
       BARN2=(NBAR1-NBAR)*WTB+NBAR
X      WRITE(6,607)
  607 FORMAT(' ','THIS IS BARN2',//)
X      WRITE(6,501) BARN2
       NBAR=(BARN2-BARN1)*WTA+BARN1
X      WRITE(6,500)
  500 FORMAT(' ','THIS IS FINAL NBAR',//)
X      WRITE(6,501) NBAR
  501 FORMAT(' ',10X,E14.8,//)
       YBAR1=Y(IA,IB2)
X      WRITE(6,608)
  608 FORMAT(' ','THIS IS YBAR1',//)
X      WRITE(6,502) YBAR1,IA,IB2
       YBAR=Y(IA,IB)
X      WRITE(6,609)
  609 FORMAT(' ','THIS IS YBAR',//)
X      WRITE(6,502) YBAR,IA,IB
       BARY1=(YBAR1-YBAR)*WTB+YBAR
X      WRITE(6,610)
  610 FORMAT(' ','THIS IS BARY1',//)
X      WRITE(6,601)BARY1
       YBAR1=Y(IA2,IB2)
X      WRITE(6,611)
  611 FORMAT(' ','THIS IS YBAR1',//)
X      WRITE(6,502) YBAR1,IA2,IB2
       YBAR=Y(IA2,IB)
X      WRITE(6,612)
  612 FORMAT(' ','THIS IS YBAR',//)
X      WRITE(6,502) YBAR,IA2,IB
       BARY2=(YBAR1-YBAR)*WTB+YBAR
X      WRITE(6,613)
  613 FORMAT(' ','THIS IS BARY2',//)
X      WRITE(6,601) BARY2
       YBAR=(BARY2-BARY1)*WTA+BARY1
X      WRITE(6,600)
  600 FORMAT(' ','THIS IS FINAL YBAR',//)
X      WRITE(6,601) YBAR
  601 FORMAT(' ',10X,E14.8,//)
  502 FORMAT(' ',10X,E14.8,5X,'ROW=',I3,1X,'COL=',I3)
C REMEMBER SIMULATION IS DONE IN COMPUTER UNITS SO NO NEED T
C**** DIVIDE BY 100.0 SINCE SUBR. DAC CONVERTS BY ITSELF IN
X      WRITE(6,55555) IFLAG
55555 FORMAT(' ',5X,'IFLAG=',I1,//)
C MAGNITUDE SCALING OF N
       NMAX=4.195E+07
       NDIM=NBAR*(9.428E+10)
       IF(IFLAG.EQ.0) NSCAL=NDIM/NMAX
       IF(IFLAG.EQ.1) NBSCAL=NDIM/NMAX
C MAGNITUDE SCALING OF Y
       YMAX=1.608E+05
       YDIM=YBAR*(17.87E+07)
       IF(IFLAG.EQ.0) YSCAL=YDIM/YMAX
       IF(IFLAG.EQ.1) YBSCAL=YDIM/YMAX
X      WRITE(6,901) NDIM,YDIM
  901 FORMAT(' ','NDIM=',E14.6,5X,'YDIM=',E14.6,//)
X      WRITE(6,5001) X01DOT,Y01DOT
 5001 FORMAT(' ','X01DOT=',E14.6,'Y01DOT=',E14.6,//)
X      WRITE(6,5000) X02DOT,Y02DOT
 5000 FORMAT(' ','X02DOT=',E14.6,'Y02DOT=',E14.6,//)
       IF(IFLAG.EQ.0) IFLAG=1;ALPHA=-ALPHA;GO TO 555
X      WRITE(6,900) NSCAL,YSCAL,NBSCAL,YBSCAL
  900 FORMAT(' ','NSCAL=',E14.6,2X,'YSCAL=',E14.6,2X,'NBSCAL
     6'YBSCAL=',E14.6,//)
  804 CALL DAC(1,X01DOT,2,Y01DOT,5,Y02DOT,6,X02DOT,3,NSCAL,4
     6CAL,8,YBSCAL)
C MANUAL DIGITAL SWITCH'0' AND '1'
```

```
   15 IF(TEST(1).GT.0) GO TO 16
      CALL HOLD
   17 IF(TEST(1).LT.0) GO TO 17
      CALL COMPUTE
   16 IF(TEST(3).GT.0) IFLAG=0;GO TO 111
      CALL RESET(1000)
      PAUSE
      GO TO 115
      END
¬LOAD XR,MAP
¬DATA
*
*
*
*                              THIS IS Y ARRAY
*
*
*
-0.1400E-03-0.1263E-03-0.1160E-03-0.1058E-03-0.9753E-04-0.90
-0.2400E-03-0.2112E-03-0.1897E-03-0.1681E-03-0.1508E-03-0.13
-0.3200E-03-0.2762E-03-0.2433E-03-0.2104E-03-0.1841E-03-0.16
-0.3800E-03-0.3225E-03-0.2793E-03-0.2362E-03-0.2016E-03-0.17
-0.4000E-03-0.3337E-03-0.2840E-03-0.2342E-03-0.1945E-03-0.15
-0.3500E-03-0.2870E-03-0.2397E-03-0.1925E-03-0.1547E-03-0.12
-0.2600E-03-0.2079E-03-0.1689E-03-0.1299E-03-0.9863E-04-0.70
-0.1300E-03-0.9384E-04-0.6671E-04-0.3959E-04-0.1789E-04 0.20
 0.4000E-04 0.5507E-04 0.6637E-04 0.7767E-04 0.8671E-04 0.95
 0.2700E-03 0.2508E-03 0.2364E-03 0.2221E-03 0.2105E-03 0.20
 0.5000E-03 0.4507E-03 0.4137E-03 0.3767E-03 0.3471E-03 0.32
 0.7000E-03 0.6225E-03 0.5643E-03 0.5062E-03 0.4596E-03 0.41
 0.8500E-03 0.7500E-03 0.6750E-03 0.6000E-03 0.5400E-03 0.48
 0.9000E-03 0.7844E-03 0.6977E-03 0.6110E-03 0.5416E-03 0.47
 0.8200E-03 0.7159E-03 0.6378E-03 0.5597E-03 0.4973E-03 0.44
 0.6250E-03 0.5579E-03 0.5075E-03 0.4572E-03 0.4169E-03 0.38
 0.4500E-03 0.4089E-03 0.3781E-03 0.3473E-03 0.3226E-03 0.30
 0.3000E-03 0.2781E-03 0.2616E-03 0.2452E-03 0.2321E-03 0.22
 0.1700E-03 0.1673E-03 0.1652E-03 0.1632E-03 0.1615E-03 0.16
 0.6000E-04 0.6822E-04 0.7438E-04 0.8055E-04 0.8548E-04 0.90
-0.2000E-04-0.3562E-05 0.8767E-05 0.2110E-04 0.3096E-04 0.40
-0.5000E-04-0.3493E-04-0.2363E-04-0.1233E-04-0.3288E-05 0.50
-0.6000E-04-0.4904E-04-0.4082E-04-0.3260E-04-0.2603E-04-0.20
-0.5000E-04-0.4699E-04-0.4473E-04-0.4247E-04-0.4065E-04-0.39
-0.1000E-04-0.2096E-04-0.2918E-04-0.3740E-04-0.4397E-04-0.50
*
*
*
*                              THIS IS N ARRAY
*
*
*
 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.6000E-04 0.60
 0.1100E-03 0.1036E-03 0.9786E-04 0.9280E-04 0.8890E-04 0.85
 0.1390E-03 0.1278E-03 0.1176E-03 0.1087E-03 0.1019E-03 0.95
 0.1530E-03 0.1349E-03 0.1186E-03 0.1042E-03 0.9308E-04 0.82
 0.1400E-03 0.1197E-03 0.1012E-03 0.8497E-04 0.7249E-04 0.60
 0.7000E-04 0.5728E-04 0.4572E-04 0.3561E-04 0.2780E-04 0.20
-0.5000E-04-0.4618E-04-0.4272E-04-0.3968E-04-0.3734E-04-0.35
-0.1750E-03-0.1536E-03-0.1342E-03-0.1172E-03-0.1041E-03-0.91
-0.3000E-03-0.2598E-03-0.2238E-03-0.1913E-03-0.1667E-03-0.14
-0.4100E-03-0.3528E-03-0.3008E-03-0.2552E-03-0.2201E-03-0.18
-0.4420E-03-0.3880E-03-0.3294E-03-0.2824E-03-0.2462E-03-0.21
-0.4250E-03-0.3785E-03-0.3272E-03-0.2823E-03-0.2476E-03-0.21
-0.3740E-03-0.3300E-03-0.2900E-03-0.2550E-03-0.2280E-03-0.20
-0.2800E-03-0.2520E-03-0.2266E-03-0.2043E-03-0.1872E-03-0.17
-0.1500E-03-0.1373E-03-0.1257E-03-0.1156E-03-0.1078E-03-0.10
-0.4500E-03-0.4373E-04-0.4257E-04-0.4156E-04-0.4078E-04-0.40
 0.4200E-04 0.3640E-04 0.3132E-04 0.2687E-04 0.2343E-04 0.20
 0.1100E-03 0.9728E-04 0.8572E-04 0.7561E-04 0.6780E-04 0.60
 0.1400E-03 0.1247E-03 0.1109E-03 0.9873E-04 0.8936E-04 0.80
 0.1320E-03 0.1193E-03 0.1077E-03 0.9761E-04 0.8980E-04 0.82
 0.1200E-03 0.1060E-03 0.9229E-04 0.8217E-04 0.7358E-04 0.65
 0.1020E-03 0.8750E-04 0.7432E-04 0.6279E-04 0.5390E-04 0.45
```

```
 0.7500E-04 0.6355E-04 0.5315E-04 0.4405E-04 0.3702E-04 0.30
 0.4500E-04 0.3864E-04 0.3286E-04 0.2780E-04 0.2390E-04 0.20
 0.9000E-05 0.1053E-04 0.1191E-04 0.1313E-04 0.1406E-04 0.15
P040   0.1600
P052   0.1600
P000   0.1511
P025   0.2860
P002   0.0803
P033   0.2860
P004   0.0404
P005   0.0052
P006   0.1660
P010   0.2379
P011   0.2383
P012   0.4717
P013   0.0250
P015   0.5607
P016   0.1340
P020   0.0920
P021   0.0097
P022   0.3576
P053   0.0905
P027   0.1750
P055   0.1497
P050   0.0337
P051   0.4380
P056   0.0092
P057   0.9540
P024   0.1581
P054   0.2860
P026   0.0803
P001   0.1750
P030   0.0404
P045   0.0920
P031   0.0052
P023   0.0905
P034   0.1660
P003   0.2860
P046   0.4717
P032   0.2379
P035   0.2383
P047   0.1497
P036   0.0097
P037   0.0250
P041   0.1340
P043   0.5607
P044   0.3576
P007   0.0337
P014   0.0092
P042   0.1511
P017   0.1581
A001
D001
A002
A003
D003
A201
A006
A005
D005
A010
A014
A016
A013
D013
A017
D017
A022
A203
A112
A060
A053
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D053
A206
A200
A051
D051
A057
D057
A202
A035
D035
A026
A027
D027
A044
A034
A033
D033
A030
A036
A041
D041
A043
D043
A042
A104
A052
A007
D007
A205
A204
A065
D065
A214
A061
D061
A211
A066
A056
A024
A216
A213
A207
A064
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A212

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Path keeping control
Distance keeping control
Interaction effects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study investigates the maneuvering of ships involved in the replenishment at sea operation under calm water conditions.

Two sets of linear differential equations of motion of a ship in three degrees of freedom are implemented for an analog-digital simulation (hybrid operation). Mainly a two phase hybrid simulation is carried out.

In the first part the real-time dynamic response of a single ship is obtained. Small perturbations, resulting from small

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changes in rudder angle and propeller RPM, are studied.

In the second part interaction forces and moments are applied only to the leading ship as it is overtaken by the tracking ship. Thus the response of the leading ship is of primary interest on this phase.

Finally interaction forces and moments are applied to both leading and tracking ship. Thus the complete response of the UNREP operation is obtained.